GE 136C: Summer 2025 Field Guide

History and Geology of Central Arizona

A view of the Verde Valley (Yavapai: Matk'amvaha) from the Mogollon Rim looking south towards Phoenix. The lushness of the valley is attributed to the Verde River, one of the last free-flowing river systems in Arizona. It provides crucial habitat for fish and wildlife, fresh water for local agricultural production, viniculture, and drinking water to more than 2 million people.

Instructor: Joe Kirschvink
TAs: Nick Anderson
Cover Photo: Nick Anderson

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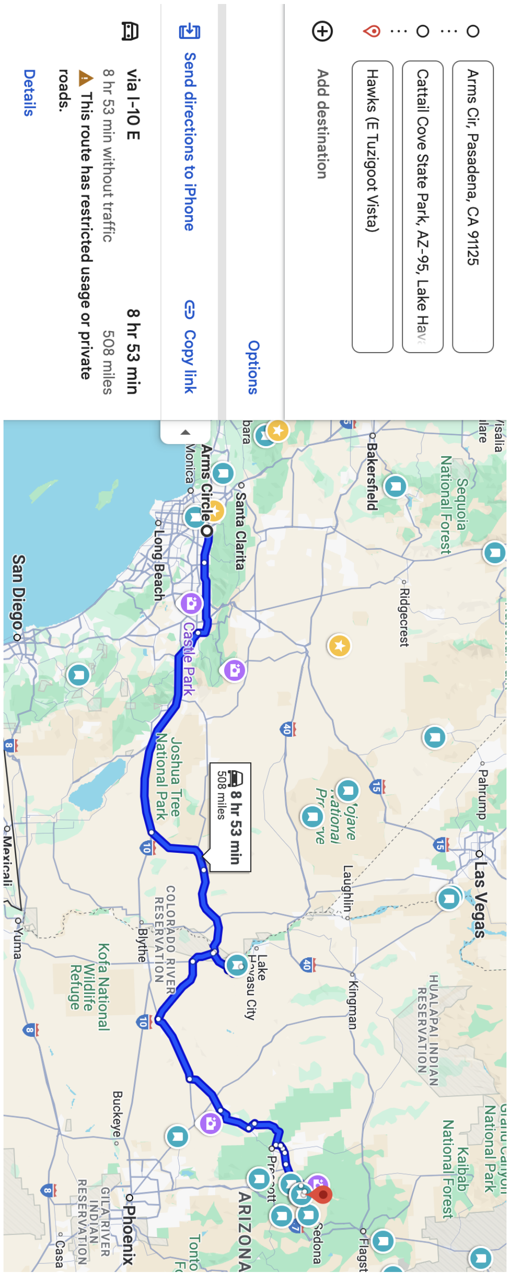
1. Routes

1.1 Day 1: Friday May 30, 2025



Arms Cir, Pasadena, CA 91125

Cattail Cove State Park, AZ-95, Lake Hav

Hawks (E Tuzigoot Vista)

Add destination

Options
Send directions to iPhone
Copy link

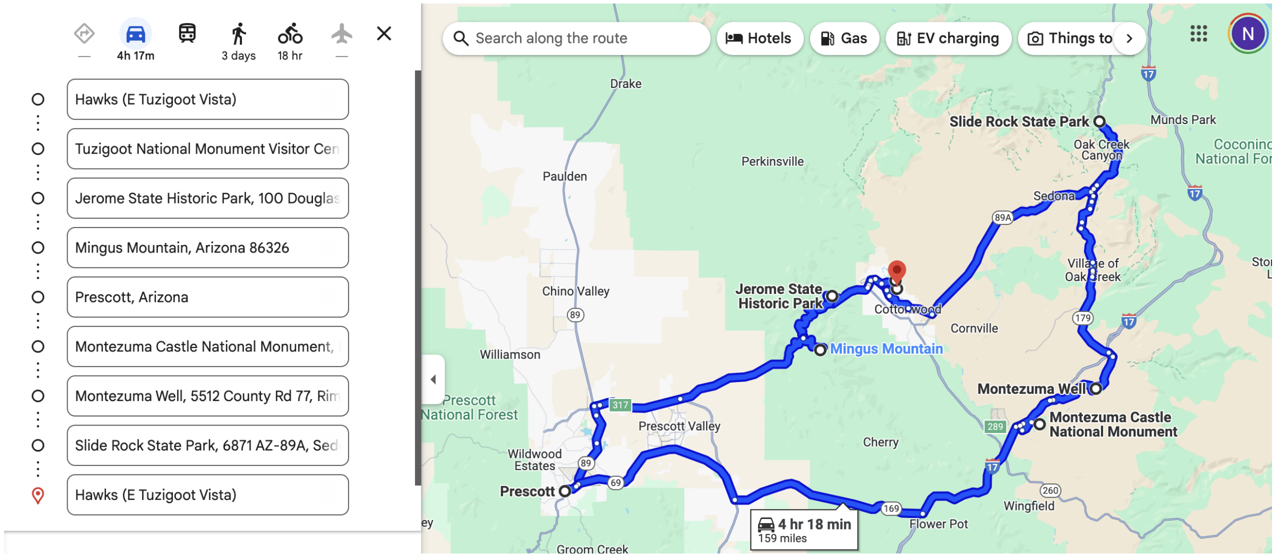
via I-10 E **8 hr 53 min**

8 hr 53 min without traffic 508 miles

⚠ **This route has restricted usage or private roads.**

Details
8 hr 53 min
508 miles
Arms Circle
Santa Clarita
Bakersfield
Long Beach
San Diego
Sequoia National Forest
Ridgecrest
Castle Park
Joshua Tree National Park
Mojave National Preserve
Pahrump
Las Vegas
Laughlin
Lake Havasu City
Kingman
COLORADO RIVER RESERVATION
Blythe
Mexicali
Yuma
Kofa National Wildlife Refuge
HUALAPAI INDIAN RESERVATION
Grand Canyon National Park
Kaibab National Forest
Buckeye
Prescott
Sedona
Flagst
ARIZONA
Phoenix
GILA RIVER INDIAN RESERVATION
Casa
Tonto

1.2 Day 2: Saturday May 31, 2025



Hawks (E Tuzigoot Vista)

Tuzigoot National Monument Visitor Cen

Jerome State Historic Park, 100 Douglas

Mingus Mountain, Arizona 86326

Prescott, Arizona

Montezuma Castle National Monument,

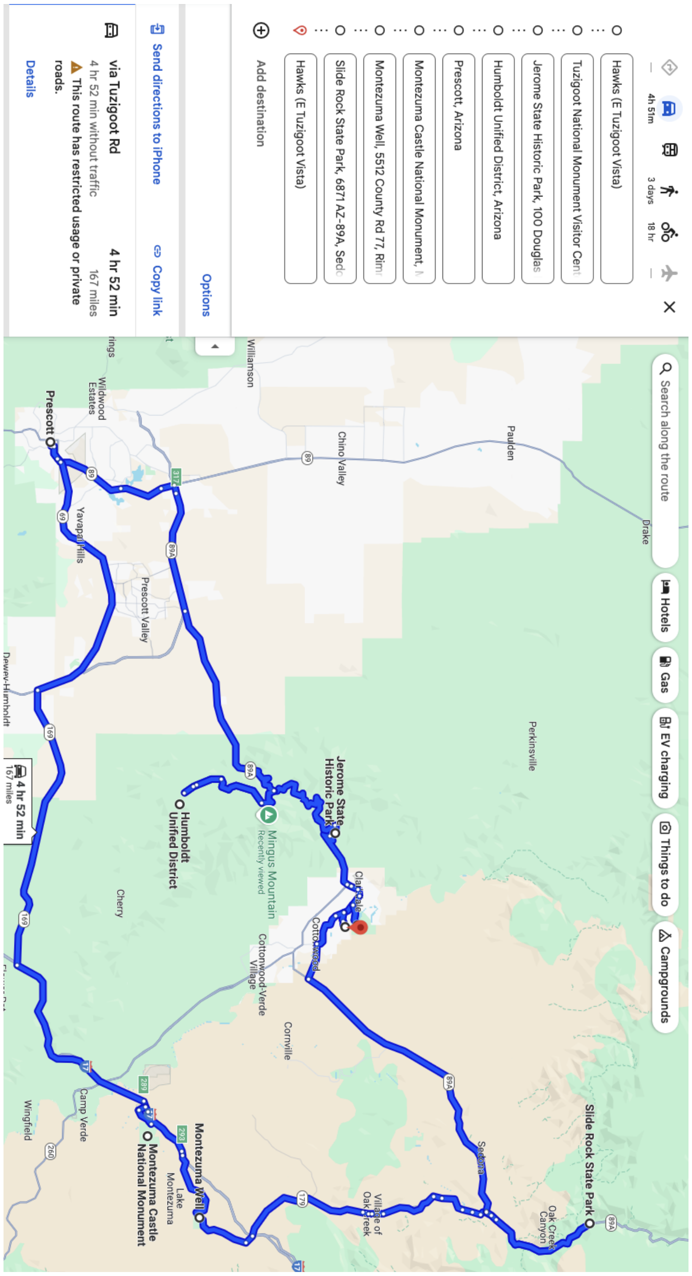
Montezuma Well, 5512 County Rd 77, Rim

Slide Rock State Park, 6871 AZ-89A, Sed

Hawks (E Tuzigoot Vista)

—
4h 17m
3 days
18 hr
—
Search along the route
Hotels
Gas
EV charging
Things to
N
Drake
Paulden
Perkinsville
Slide Rock State Park
Munds Park
Oak Creek Canyon
Coconino National For
Sedona
89A
Chino Valley
89
Jerome State Historic Park
Cottonwood
Village of Oak Creek
179
17
Cornville
Williamson
Mingus Mountain
Prescott National Forest
317
Prescott Valley
Montezuma Well
Montezuma Castle National Monument
289
Wildwood Estates
Cherry
Prescott
69
260
Wingfield
4 hr 18 min
159 miles
169
Flower Pot
Groom Creek

1.3 Day 3: Sunday June 1, 2025


4h 51m
3 days
18 hr
Search along the route
Hotels
Gas
EV charging
Things to do
Campgrounds
Drake
Paulden
Chino Valley
Williamson
Perkinsville
Wildwood Estates
Prescott
Yavapai Hills
Prescott Valley
Dewey-Humboldt
Jerome State Historic Park
Mingus Mountain
Recently viewed
Humboldt Unified District
Cherry
Clarkdale
Cottonwood
Cottonwood-Verde Village
Cornville
Sedona
Slide Rock State Park
Oak Creek Canyon
Village of Oak Creek
Lake Montezuma
Montezuma Well
Montezuma Castle National Monument
Camp Verde
Wingfield
4 hr 52 min
167 miles

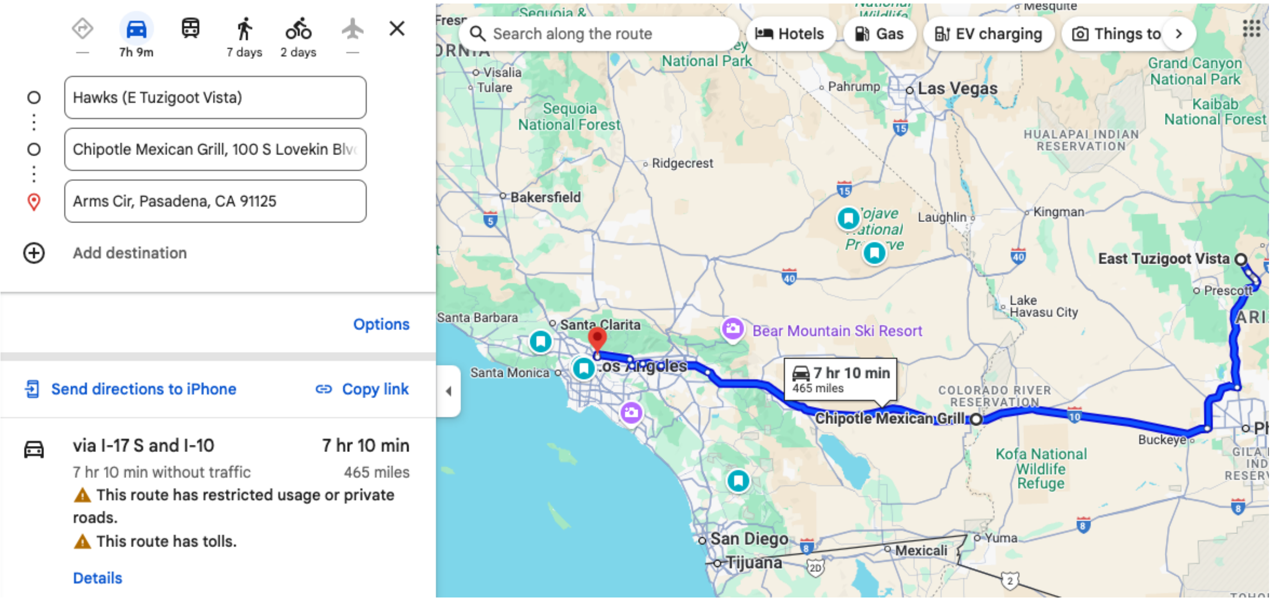
Hawks (E Tuzigoot Vista)
Tuzigoot National Monument Visitor Cent
Jerome State Historic Park, 100 Douglas
Humboldt Unified District, Arizona
Prescott, Arizona
Montezuma Castle National Monument,
Montezuma Well, 5512 County Rd 77, Rim
Slide Rock State Park, 6871 AZ-89A, Sedo
Hawks (E Tuzigoot Vista)
Add destination

Options

Send directions to iPhone
Copy link

via Tuzigoot Rd **4 hr 52 min**
4 hr 52 min without traffic 167 miles
⚠ This route has restricted usage or private roads.
Details

1.4 Day 4: Monday June 2, 2025



Hawks (E Tuzigoot Vista)

Chipotle Mexican Grill, 100 S Lovekin Blv

Arms Cir, Pasadena, CA 91125

Add destination

via I-17 S and I-10 — 7 hr 10 min

7 hr 10 min without traffic — 465 miles

⚠ This route has restricted usage or private roads.

⚠ This route has tolls.

—
7h 9m
7 days
2 days
—
Options
Send directions to iPhone
Copy link
Details
Search along the route
Hotels
Gas
EV charging
Things to
7 hr 10 min
465 miles
East Tuzigoot Vista
Chipotle Mexican Grill
Los Angeles
Santa Clarita
Santa Barbara
Santa Monica
Bear Mountain Ski Resort
San Diego
Tijuana
Mexicali
Yuma
Buckeye
Prescott
Lake Havasu City
Kingman
Laughlin
Las Vegas
Pahrump
Ridgecrest
Bakersfield
Visalia
Tulare
Sequoia National Forest
Grand Canyon National Park
Kaibab National Forest
HUALAPAI INDIAN RESERVATION
COLORADO RIVER RESERVATION
Kofa National Wildlife Refuge
Mesquite

2. Trip Schedule

Day	Approximate Time (PDT)	Activity	Talks	Duration	Bathroom	Gas	Drive Time
Day 1 - 2/14	7:00	Meet at Arms Circle/ Caltech		1:00	X		
	8:00	Leave Arms Circle					1:20
	9:20	Lake Elsinore - Elm Grove Beach	Thalhammer	0:30	X		0:45
	10:35	Pala Mining District	Sanchez	0:30			0:45
	11:50	Palomar Observatory and Lunch	Langley/ Sowell/ Stenmark/ Oke	2:00	X		0:55
	14:45	Julian Pie Company	Heiny	0:45	X	X	0:50
	16:20	Pictographs Trail Head	Hannahs	2:00			0:45
	19:05	Agua Caliente Camp	Seeger/ Williams	1:00	X		0:40
Day 2 - 2/15	8:30	Leave Agua Caliente			X		1:00
	9:30	Anza Borrego Visitor Center		0:30	X	X	0:30
	10:30	Calcite Slot Mine		1:00			0:50
	12:20	Painted Canyon		0:30			0:30
	13:20	Durmid / Salt Creek Beach Campground	Kalucha/ Menezes/ Mullahoo/ Stone/ Bednarick/ Bennett	1:30	X		0:15
	15:05	Bombay Beach		0:15	X		0:25
	15:45	Slab City / Salvation Mountain	Alcabes	0:30	X		0:25
	16:40	Obsidian Butte	Chriem/ Artymowicz/ Chastain/ Keebler	0:30		X	0:35
	17:45	Algodones Dunes / Glamis Flats	Schmeer/ Horak	0:40			0:50
	19:15	Walter's Camp	Hunady	1:50	X		
Day 3 - 2/16	7:30	Leave Walters Camp	McCann		X		1:15
	8:45	Hauser Geode Beds	Westercamp/ Vescu	1:00			0:55
	10:40	Opal Hill Mine / Wiley's Well		0:30	X		1:45
	12:55	Cholla Cactus Garden	Aguilar/ Shivji	0:30	X		0:35
	14:00	Bagly Stone / Wall St Mill / Barker Dam		0:30	X		0:30
	15:00	Joshua Tree Visitor Center	Li	0:30	X		2:30
	18:00	Arrive at Arms Circle					

Hawk's Hideaway Campground Information:

- **Location:** 34.76090480158216 N, -112.02488436470671 W
- **Host Contact:** Vicky Hunt / +1 (928) 821-1092
- **Check In:** 2:00 PM
- **Check Out:** Before 12:00 PM

Hawk's Hideaway Campground Regulations:

- **Water:** Potable drinking water is not available at this listing. Bring your own water or purify from hose.
- **Fire Safety:** Campfires are allowed at this listing. Be fire safe – always check state and local fire regulations before having a campfire and know how to properly extinguish your fire.
- **Campfire Rules:** Campfires are allowed only in designated firepits and only if there is no fire ban in effect. Annual fire restrictions are imposed by the national forest service and apply to private property as well. We have no control over this.
- **Fire Materials:** Campfires are for wood debris or charcoal only (dead wood is abundant and easy to gather). Cooking on a campfire is allowed but do not burn plastic or trash of any kind. Do not leave fire unattended and make sure it is completely out when you leave.
- **Restroom:** A toilet is available at this listing (portable toilet).
- **Pets:** Pets are allowed at this listing.
- **Shower:** There is no shower available at this listing.
- **Waste Disposal:** Waste disposal is available at this listing (trash bin). Trash bins are located on the left as you leave the property.
- **Kitchen:** Kitchen and cooking equipment are not available.
- **Quiet Hours:** Be considerate and courteous to other campers. No loud music, conversation or noise after 11 pm IF there are other campers present. If you want to whoop it up with a bunch of friends, book all the sites. Otherwise, please keep late night noise to a minimum.
- **Wildlife:** Wildlife abounds and we like it that way. There is absolutely no hunting, trapping, shooting, or killing of the animals (excluding insects – feel free to swat away the bugs).

GENERAL CONDITIONS
For
Education Fee Waiver
With special reference to the Paleontological Resources Preservation Act of 2009

United States Department of the Interior
National Park Service
Petrified Forest National Park

1. **Collection of specimens (including materials)** - No park resources may be collected. All collected park resources remain federal property, regardless of where the resources reside, who discovered or collected them, or who assumes responsibility for their care, and removal of any resources from federal land without an active permit constitutes theft of federal property.

The general conditions for specimen collections are:

- Collection of archeological resources without a valid Federal Archeology Permit is prohibited.
- Collection of paleontological resources is prohibited without a valid Scientific Research and Collection permit.
- Collection of federally listed threatened or endangered species without a valid U.S. Fish and Wildlife Service endangered species permit is prohibited.
- Collection of federally listed birds or bird feathers under the Migratory Bird Treaty Act (MBTA) without a valid U.S. Fish and Wildlife Service migratory bird special purpose salvage permit is prohibited.

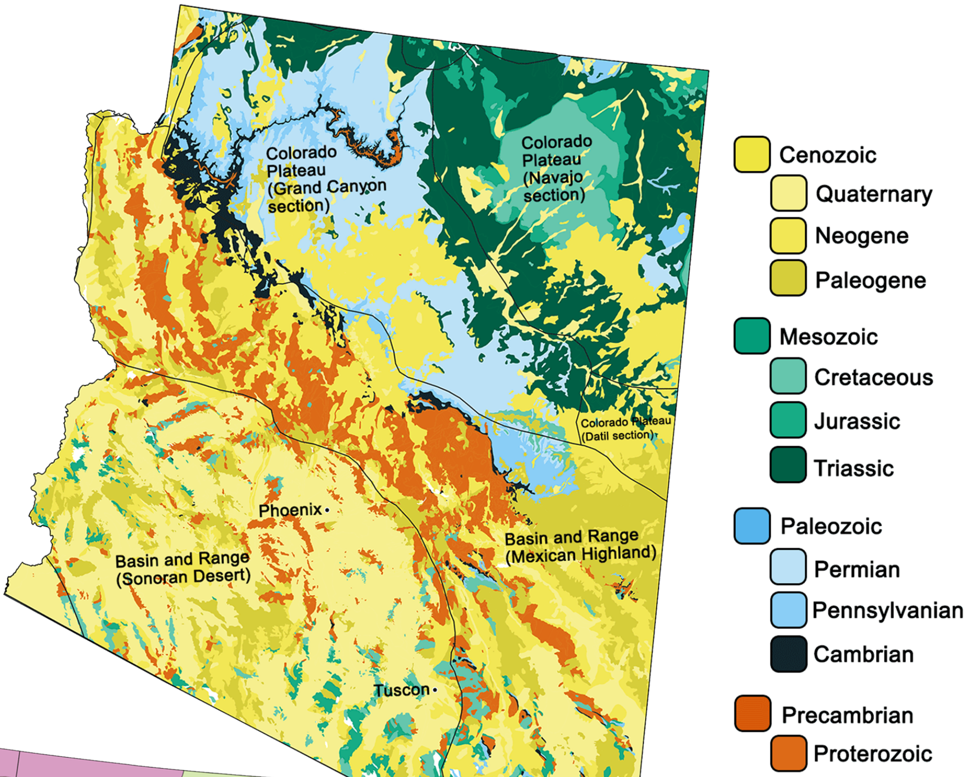
2. **Ground disturbance** – No ground disturbance is allowed in the park and the use of rock hammers and other tools is prohibited.

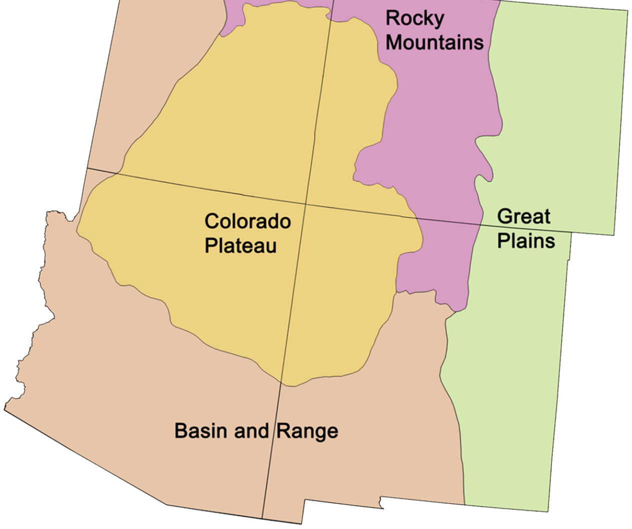
3. **Wayfinding** – The use of GPS and wayfinding technology is allowed in the park, but coordinates to sensitive paleontological, geological, archaeological, biological, and historic resources is not to be shared with the public not covered by the educational fee waiver. Certain types of resource-related locality data are exempt from the Freedom of Information Act and should not be disseminated.

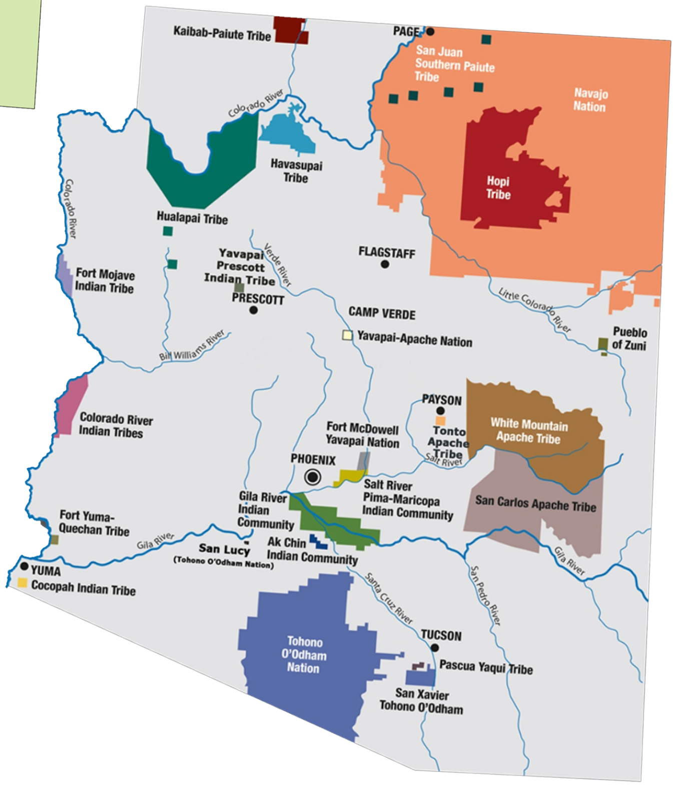
4. **Photography and social media**- Photography in the park is encouraged but take care in posting photographs to social media that contain identifiable landmarks and metadata associated with locality data.

7. **Reporting** – Please report resources to NPS staff as necessary. Take photographs and note the location of items in order to share this information to relevant park staff.

8. **Access to park and restricted areas** - Travel within the park is restricted to only those methods that are available to the general public unless otherwise specified in additional stipulations associated with this waiver. Use of roads not open to the public and entry into closed areas require special permission on a case by case basis. Approval for any activity is contingent on the park being open and staffed for required operations. No entry into restricted areas is allowed unless authorized in additional park specific stipulations attached to this waiver.


Colorado Plateau (Grand Canyon section)
Colorado Plateau (Navajo section)
Colorado Plateau (Datil section)
Phoenix
Basin and Range (Sonoran Desert)
Basin and Range (Mexican Highland)
Tuscon
Cenozoic
Quaternary
Neogene
Paleogene
Mesozoic
Cretaceous
Jurassic
Triassic
Paleozoic
Permian
Pennsylvanian
Cambrian
Precambrian
Proterozoic


Rocky Mountains
Colorado Plateau
Great Plains
Basin and Range


Kaibab-Paiute Tribe
PAGE
San Juan Southern Paiute Tribe
Navajo Nation
Colorado River
Havasupai Tribe
Hopi Tribe
Hualapai Tribe
FLAGSTAFF
Yavapai Prescott Indian Tribe
Verde River
Fort Mojave Indian Tribe
PRESCOTT
CAMP VERDE
Little Colorado River
Yavapai-Apache Nation
Pueblo of Zuni
Bill Williams River
PAYSON
Colorado River Indian Tribes
Fort McDowell Yavapai Nation
Tonto Apache Tribe
White Mountain Apache Tribe
Salt River
PHOENIX
Salt River Pima-Maricopa Indian Community
Gila River Indian Community
San Carlos Apache Tribe
Fort Yuma-Quechan Tribe
Gila River
San Lucy (Tohono O'Odham Nation)
Ak Chin Indian Community
YUMA
Cocopah Indian Tribe
Santa Cruz River
San Pedro River
Tohono O'Odham Nation
TUCSON
Pascua Yaqui Tribe
San Xavier Tohono O'Odham

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	Latest Tertiary	anhydrous basaltic volcanism	Metalum. Alkalic	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu
Galiuro	Late (Whipple)	18-13	Late Tertiary	volcanics & local epizonal stocks	Metalum-inous Alkalic	Cu-Au-Ag in veins; epithermal Au-Ag veins	Oatman, Mammoth, Rowley
	Middle (Datil)	28-18	Mid-Tertiary	alkali-calcic ignimbritic volcanics & plutons	Metaluminous Alkali-calcic	Pb-Zn-Ag F veins, replace.; epithermal	Silver (Red Cloud m.), Castle Dome, Stanley, Aravaipa
	Early (South Mountain	30-22	Mid-Tertiary	calc-alkalic volcanics & plutons	Metalum. Calc-alkalic	Au +/- Cu-W veins & disseminated	Little Harquahala, Kofa
	Earliest (Mineta)	38-28	Mid-Tertiary	mostly within 'volcanic gap"	-	Uranium, clay, exotic copper	Ajo Cornelia, Copper Butte (from Ray)
Laramide	Late (Wilderness)	55-43	Early Tertiary	2-mica, garnet-muscovite granitic stocks, sills, dikes	Peralum. Calcic, Calc-alkalic	Au dissem. & qtz veins; W veins,	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin, Copperstone
	Middle (Morenci)	65-55	Cretaceous-Tertiary	granodiorite - quartz monzonite porphyry stocks, NE to ENE-striking dike swarms	Metaluminous Calc-alkalic	large disseminated porphyry Cu systems, local skarns & veins, fringing Zn-Pb-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior
	Early (Tombstone)	85-65	Late Cretaceous	qtz. monz. porph. stocks; ash flows	Metalum. Alkali-calcic	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero
	Earliest (Hillsboro)	89-85	mid-Cretaceous	Volcanics, small stocks	Metalum. Alkalic	Cu-Au hydrothermal	Hillsboro, NM
Sevier		145-89	mid-Cretaceous			Sedimentary rocks	Bisbee Group sediments
Nevadan	Late	160-145	Late Jurassic	volcanics			
	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)
	Early	230-205	Late Triassic	Fluid flow thru sedimentary rocks	Metalum. Alkalic	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley
Alleghenian (Ouachita)		325-220	Miss. – Triassic	None	-	U in sed. rocks	Payson uranium
Acadian/ Caledonian		410-380	Devonian	None	-	Limestone	
Taconic.		490-445	Cambrian – Ord.	None	-		
Grenville		1200-900	Late Middle Proterozoic – Early Late Proterozoic	basalt flows, diabase dikes	Metalum. Alkalic	Serpentine asbestos	Sierra Ancha uranium Chrysotile (Salt R. Canyon)
"Oracle/Ruin"		1440-1335	Middle Proterozoic	K-feldspar megacrystic or porphyritic granites	Peralum. Calc-alkalic, Alkali-calcic	Pegmatites & greisens – Be, Li, Ta-Nb, U & W	White Picacho, Tungstona, Four Peaks
Mazatzal		1750-1600	Late Early Proterozoic	Basalt & rhyolite metavolc., schist	Metalum. Calcic	Cu-Zn-Ag VMS	Old Dick (Bruce)
Yavapai		1800-1775	Late Early Proterozoic	Andesite, schist, metarhyolite	Metalum. Calcic	Cu-Zn-Au VMS, Cu-Zn-Ag	Big Bug (Iron King), Verde (Jerome)
Penokean/ Hudsonian		2000-1800	Middle Late Proterozoic	Schist, banded cherty iron formation	Metalum. Calcic	BIF (Banded iron formation)	Pikes Peak iron

Table 1. Mountain building episodes in Arizona

A theory for how temperature and soil moisture in the Southwest can affect extreme weather in the Plains

Olivia Alcabes

What is convective available potential energy (CAPE) and why should we care about it?

Extreme weather is difficult to measure, as we lack sufficient observations due to the short lived and (relatively) small spatial coverage of atmospheric storms. However, predicting climatological extreme weather over land is highly important. Three environmental metrics have been shown to be good proxies for extreme weather: (1) convective available potential energy (CAPE), (2) convective inhibition (CIN), and (3) wind shear. CAPE (in this case I'm using reversible CAPE that doesn't include cloud microphysical processes or precipitation) can be calculated by lifting a near-surface air parcel up to the level of neutral buoyancy and then integrating the buoyancy difference with respect to pressure. CIN is similarly calculated as the same integral, but only to the level of free convection.

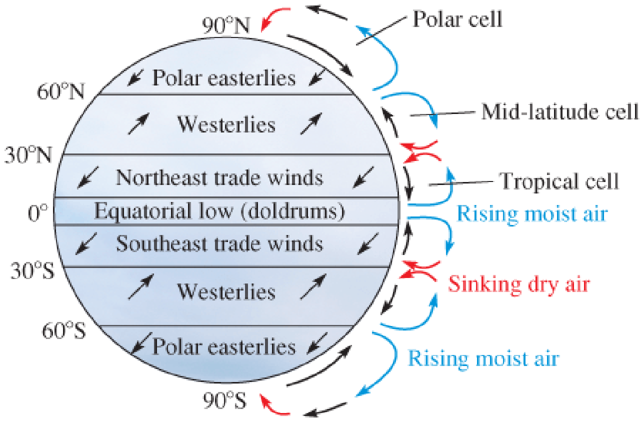
When an air parcel is able to overcome the CIN through some method such as (ex. adiabatic uplift from topography), convection can increase freely and high vertical velocities can occur. In this way, CAPE can be thought of as an upper bound for updraft speed, although it is important to note that a high CAPE value does not necessarily mean strong updrafts will occur. Additionally, there are ways that severe convective storms can occur even with low CAPE. However, correctly understanding the mechanisms behind the formation of CAPE can potentially increase our understanding of how these convective storms might form.

$$\mathrm{CAPE} = -R_d \int_{p_0}^{p_{\mathrm{LNB}}} (T_{vp} - T_{ve})\, d\log p$$

CAPE has three main mechanisms to grow:

- Radiative cooling in the free troposphere leading to instability for parcels near the surface
- Advection of high-entropy air from outside of the column, supplying increased heat & moisture & leading to more instabilities
- Diabatic heating of near-surface air from below

In this simple example, we focus on how soil moisture differences can lead to the growth of CAPE. Specifically, in the US, hot, dry air over the southwest is advected by the mean flow across the Rockies and over the great Plains.


90°N
Polar cell
60°N
Polar easterlies
Westerlies
Mid-latitude cell
30°N
Northeast trade winds
Tropical cell
0°
Equatorial low (doldrums)
Rising moist air
Southeast trade winds
30°S
Sinking dry air
Westerlies
60°S
Polar easterlies
Rising moist air
90°S

Idealized Model

Agard & Emanuel (2017) and Emanuel (2023) present a theory for how a hot, dry air mass that is advected over a moist surface can lead to a buildup of CAPE. The model is a simple single-column that starts with dry conditions and an initial temperature T0, and then is advected over a moist surface. Emanuel (2023) includes a diurnal cycle of incoming solar radiation and a soil moisture model. After the dry air is advected over the moist surface, a shallow moist boundary layer forms, with the dry air above acting as a lid. Then, as the sun rises, radiative heating increases surface fluxes and the boundary layer deepens and moistens, leading to an increase in CAPE and a decrease in CIN. I have included the equations for the atmospheric model here for those so inclined!

$$\rho h \frac{dD}{dt} = F_S + \rho w_e (D_0 - D), \tag{3}$$

$$\rho h \frac{dM}{dt} = F_{\mathrm{rad}} + \rho w_e (D_0 - M), \tag{4}$$

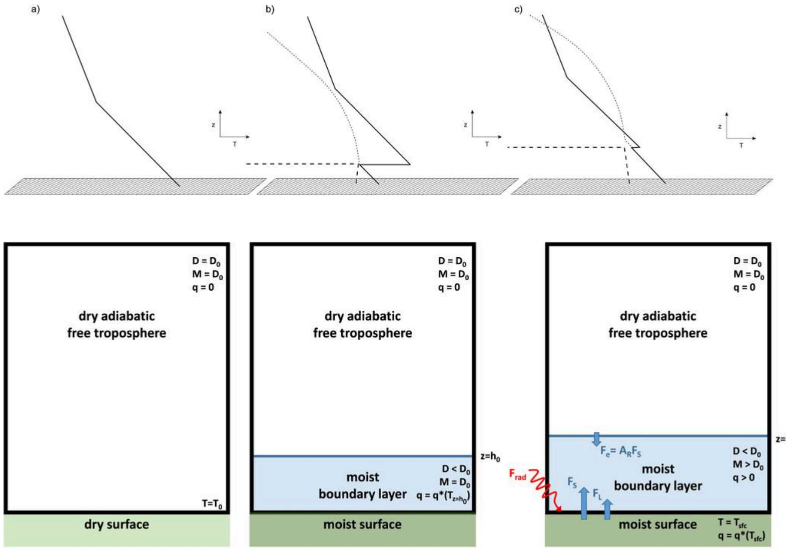
$$\frac{dh}{dt} = w_e, \tag{5}$$

$$F_S = \rho C_T v_{\mathrm{sfc}} (c_p T_{\mathrm{sfc}} - D), \tag{6}$$

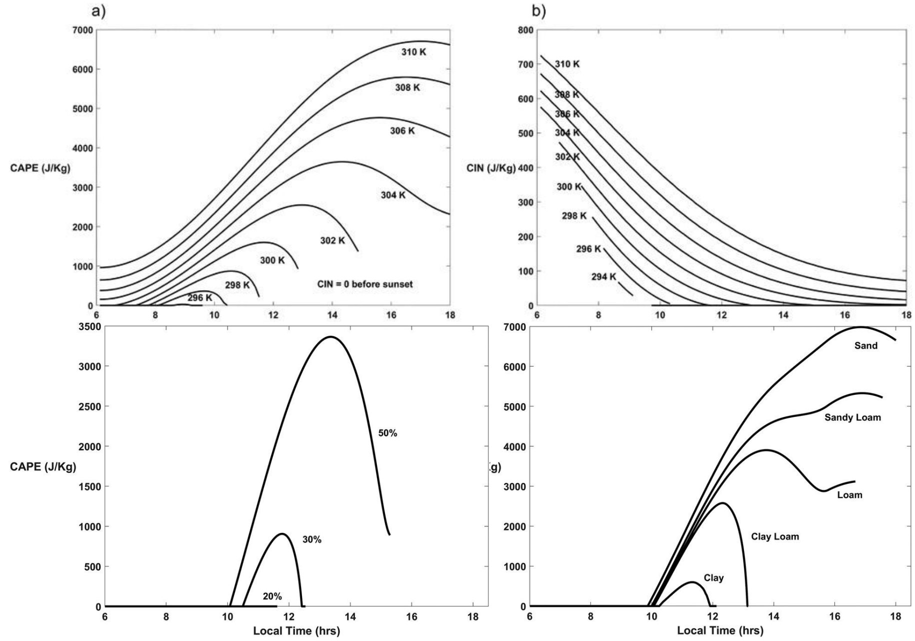
$$F_L = \alpha \rho C_T v_{\mathrm{sfc}} [L_v q^*(T_{\mathrm{sfc}}) - M + D], \quad \text{and} \tag{7}$$

$$F_S + F_L = F_{\mathrm{rad}}. \tag{8}$$

Here D is dry static energy, M is moist static energy, h is the boundary layer height, q is specific humidity, and Fs and FL are the surface sensible and latent heat fluxes. Fe is the flux due to entrainment and Frad is the flux due to incoming solar radiation.


a)
b)
c)
z
T
z
T
z
T
D = D$_0$
M = D$_0$
q = 0
dry adiabatic free troposphere
T=T$_0$
dry surface
D = D$_0$
M = D$_0$
q = 0
dry adiabatic free troposphere
z=h$_0$
D < D$_0$
M = D$_0$
moist boundary layer
q = q*(T$_{z=h_0}$)
moist surface
D = D$_0$
M = D$_0$
q = 0
dry adiabatic free troposphere
z=h
F$_e$= A$_R$F$_S$
D < D$_0$
M > D$_0$
q > 0
moist boundary layer
F$_{rad}$
F$_S$
F$_L$
moist surface
T = T$_{sfc}$
q = q*(T$_{sfc}$)

(a) pre-initialization (b) $t = 0$ (c) $t > 0$

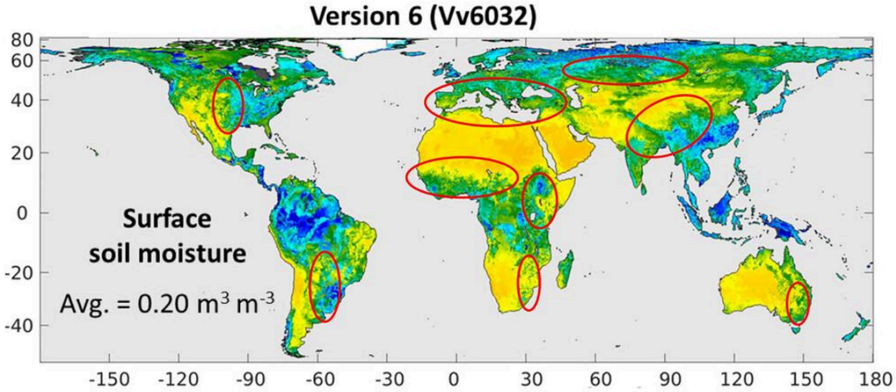


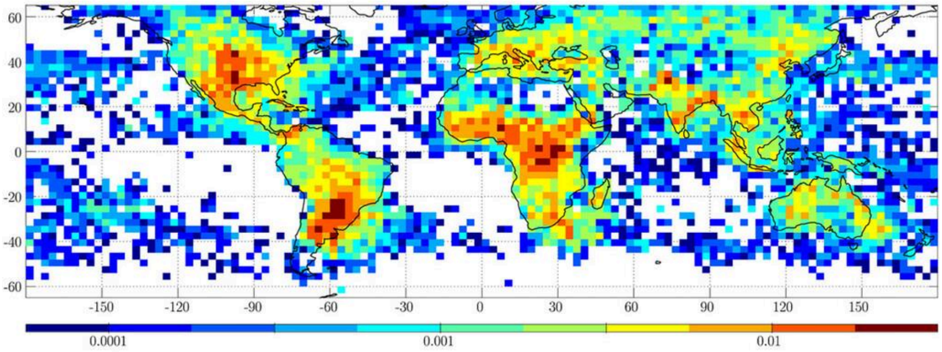
Results

Through this simple model, we can see how different conditions can affect the growth of CAPE. To the left, I show four plots: the first two illustrate the influence of the initial desert temperature T0 on the growth of CAPE and CIN. Increased desert temperatures lead to higher CAPE and CIN values that change over the course of the day. In the bottom two plots, we see how the subsurface soil saturation fraction and the type of soil impact CAPE values. Overall, soil that can flux moisture into the atmosphere for the whole day tends to more lead to higher peak CAPE values.

How we can use this simple theory to predict severe weather in the future

Although this idealized model is quite simple and contains many assumptions, there are some important takeaways. If we look at the observational record (see the below two maps), we see some evidence of the power of this theory. In the first map, surface soil moisture is plotted, with regions of high soil moisture downwind of desert regions circled. The bottom plot shows the percentage of time that soundings have detected hail (a proxy for an extreme convective storm). Qualitatively, it is true that regions with high soil moisture downwind of regions with low soil moisture do tend to be where the greatest amount of hail has been detected. If the physics described by this theory is dominant for creating strongly convective storms on land, then we can use it to think about how climate change and land use may influence extreme weather conditions in the future. Under climate change, deserts are expected to get both hotter and drier, which may lead to higher CAPE values in regions downwind. Additionally, the increase of agricultural land use and agricultural land practices in the plains and in the desert regions may have large influences on the frequency of extreme weather events, the extent to which we should work to constrain in the future (and make sure we're properly representing in our climate models!)





References

Agard, Vince, and Kerry Emanuel. "Clausius–Clapeyron Scaling of Peak CAPE in Continental Convective Storm Environments." *Journal of the Atmospheric Sciences* 74, no. 9 (September 1, 2017): 3043–54.

Emanuel, Kerry. "On the Physics of High CAPE." *Journal of the Atmospheric Sciences* 80, no. 11 (November 10, 2023): 2669–83.

Lanicci, John M., Toby N. Carlson, and Thomas T. Warner. "Sensitivity of the Great Plains Severe-Storm Environment to Soil-Moisture Distribution." *Monthly Weather Review* 115, no. 11 (November 1, 1987): 2660–73.

Romps, David M., Alexander B. Charn, Robert H. Holzworth, William E. Lawrence, John Molinari, and David Vollaro. "CAPE Times P Explains Lightning Over Land But Not the Land-Ocean Contrast." *Geophysical Research Letters* 45, no. 22 (2018): 12,623-12,630.

Tuckman, P. J., and Kerry Emanuel. "Origins of Extreme CAPE Around the World." *Journal of Geophysical Research: Atmospheres* 129, no. 22 (2024): e2024JD041833.

Cactuses of Arizona - Juni Polansky

Climate and vegetation in Arizona

cactus wren drinking nectar from a saguaro blossom

As the sixth largest state in the United States, Arizona covers almost 114,000 mi^2, and this large expanse of land encompasses several distinct climates and ecosystems. While about half of Arizona is semiarid and one-third is arid, the remaining areas, particularly at higher elevations, experience more moderate climates with greater precipitation. In major cities like Phoenix the winter months are cooler, with mean maximum temperatures around 65ºF (18ºC) and occasional bouts of precipitation that interrupt the dry periods of spring and fall. The summers are very hot with maximum average readings around 106ºF (41ºC) in Phoenix. In July, moisture-laden air from the Gulf of California and the eastern Pacific Ocean contribute to Arizona's summer monsoon season, bringing short but intense thunderstorms. Further away, the Colorado Plateau has colder winters and a semiarid climate. Higher elevation in this area and direct exposure to polar air masses produces lower temperatures (mean high/low around 46ºF /19ºF) and higher annual precipitation.

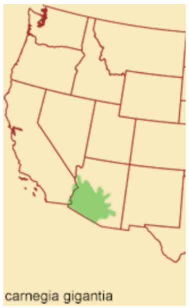
The wide diversity of climates across Arizona is mirrored by a similar degree of diversity in the state's wildlife and vegetation. About 10% of Arizona is forest, 25% is woodland, 25% is grassland, and the rest is desert shrub. Cacti grow throughout the state, but the greatest diversity of types is found at lower elevations, around 2,000 feet. They are most numerous in Pima County (in southern Arizona) and least common in Greenlee County (eastern Arizona).

Unique features of cacti!

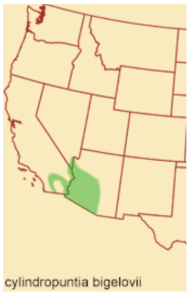
While the general structure of a cactus is fundamentally similar to most flowering plants, most cacti do *not* have leaves. Instead, they have large stems relative to the size of the rest of their body. Most of the stem is occupied by storage cells used for water retention, and the surface of the cactus is covered by a waxy, epidermal layer that prevents evaporation. While a few species, like the night-blooming cereus, have tuberous roots for water storage, most cacti possess shallow, fibrous root systems designed to absorb surface water rapidly after rainfall. Many cacti produce flowers with an inferior ovary, meaning the fruit develops below the flower parts—unlike most flowering plants, where the fruit forms above.

Carnegiea gigantea (saguaro cactus)

The *Carnegiea gigantea*, otherwise known as the saguaro, is a tree-like cactus species that is native to the Sonoran Desert that spans from northwest Mexico to the southwestern United States (including Arizona). As the largest cactus species in the United States, a saguaro can grow over forty feet tall, but despite its immense height, the saguaro is very slow growing. In the first eight years of its life a saguaro might only grow between 1 to 1.5 inches, and it can take over 200 years for the saguaro to reach its full height. This practice of slow growth allows the saguaros to survive long dry periods and outlive most humans by more than one lifetime. Saguaros typically begin flowering between the ages of 35 and 50, with large white blossoms appearing in April and May. By July, the flowers make way to scarlet fruit. The saguaro flower is the state flower of Arizona, and the fruit, traditionally harvested by Indigenous Tohono O'odham people, can be eaten raw or made into syrup and jelly. The saguaro cactus is an important keystone species, storing large amounts of water in their tissues to be used by other animals –such as bighorn sheep and jackrabbits– during periods of drought.


carnegia gigantia

Saguaro

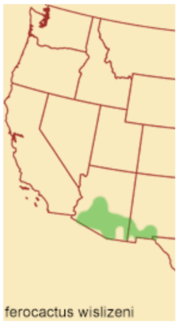

cylindropuntia bigelovii

Teddy bear cholla

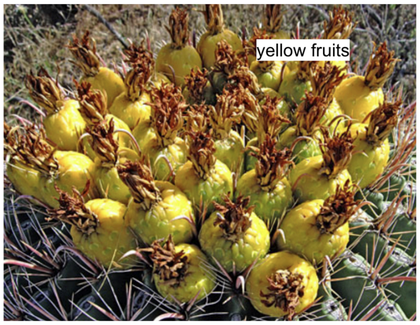
Cylindropuntia bigelovii (Teddy bear cholla)

Cylindropuntia bigelovii, otherwise known as Teddy bear cholla, is another native of the Sonoran Desert. The teddy bear cholla has short (less than 5 inches), stout, cylindrical stems covered by thick, gold-colored spines that obscure the cactus's original green coloring. Both the cactus's spines and stems can be easily removed, making it very easy to propagate the plant. Adults typically grow to about five feet in height and are often surrounded by fallen stems and spines, which aid in the plant's spread. They also often develop a woody trunk at the base several inches in diameter. The teddy bear cholla prefers exposed areas with full sun, and in the late spring months of May and June they can produce yellow-green flowers and fruits.

***Ferocactus wislizeni* (fishhook barrel/Arizona barrel)**

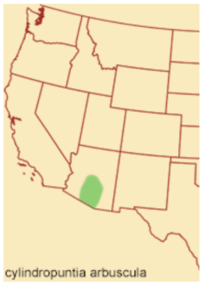


Arizona barrel cactus



The fishhook barrel cactus originated from the desert shrub habitats of the Sonoran and Chihuahuan deserts, but its habitat has expanded to include the greater Arizona, New Mexico, and Texas area. Cacti have a large columnar shape with an internal structure composed of 20-30 woody ribs. These ribs can expand during monsoon season for easier water storage, and, due to unequal growing rates between the shaded/sunny side, the cacti tend to lean in a southwestern-orientation over time.

The fishhook cactus can produce orange/red flowers, which later result in scaly, oval-shaped yellow fruits. The fleshy fruits contain thousands of seeds that were traditionally consumed or traded by Indigenous peoples of the Southwest. The spines of the cacti can be used for hunting or turned into hooks for fishing. The fleshy tissues of the cacti are also consumed by bighorn sheep during droughts.



Arizona pencil cholla

Spineless fruits

***Cylindropuntia arbuscula* (Arizona pencil cholla)**

Originating from the Sonoran desert, the pencil cholla can be found in the south central part of the state from Phoenix to the border with Mexico. As its name suggests, the pencil cholla has slender stems about half an inch thick, often green or tinged purple. The pencil cholla's spines are yellow-brown in color, while its flowers, which appear between April-June, are spineless and are yellow to bronze in color. The fruits were historically harvested and roasted by Indigenous peoples as a food source.

Impacts of climate change on native cacti populations

Struggling saguaro

Climate change has led to extreme temperature fluctuations and disrupted established rainfall patterns. Since the start of the 20th century, temperatures in Arizona have risen by approximately 2.5°F, and they are projected to continue rising throughout the next century. This warming trend has accelerated soil evaporation and plant transpiration, speeding up the Earth's water cycle. The resulting increase in evapotranspiration has dried out soils, worsening drought conditions and placing additional stress on native plant and animal communities. These drier conditions have also heightened the frequency and severity of wildfires, further damaging Arizona's desert ecosystems. As slow-growing native plants like cacti struggle to adapt, fast-growing invasive weeds are taking over, competing for limited water and contributing to the "grassification" of the Sonoran Desert. Though not as large as forests or oceans, these ecosystems play a significant role in the global carbon cycle, providing one of the largest terrestrial carbon sinks. Therefore, the consequences of climate change in Arizona extend beyond regional biodiversity loss—disruptions to desert plant life could have cascading effects on global carbon dynamics, amplifying the risks of climate change worldwide.

Sources:
[1] Arizona State University. (n.d.). *UA Campus Arboretum*. Retrieved May 21, 2025, from https://arboretum.arizona.edu/
[2] American Southwest. (n.d.). *Cacti of Arizona*. Retrieved May 21, 2025, from https://www.americansouthwest.net/plants/cacti/arizona.html
[3] Benson, L. (1957). *The cactus-ant relationship in the Sonoran Desert*. *Ecology*, *38*(3), 488–495.
[4] Mooney, C. (2023, October 30). *The slow death of a desert giant*. Yale Climate Connections. https://yaleclimateconnections.org/2023/10/the-slow-death-of-a-desert-giant/
[5] U.S. Environmental Protection Agency. (n.d.). *Climate change connections: Arizona's saguaro cactus*. Retrieved May 21, 2025, from https://www.epa.gov/climateimpacts/climate-change-connections-arizona-saguaro-cactus
[6] Turner, R. M., Bowers, J. E., & Burgess, T. L. (2005). *Sonoran desert plants: An ecological atlas*. University of Arizona Press.

Unique Trees of Arizona: Indigenous Knowledge and Ethnobotanical Uses

Gabrielle Chang | Ge 136c

Indigenous groups such as the Yavapai, Western Apache, Hopi, and Tohono O'odham have long thrived in central Arizona, developing ethnobotanical knowledge over generations. Their use of native trees for food, medicine, tools, and ritual reflects a deep understanding of local ecosystems. This report examines the traditional uses of five tree species and their roles in Indigenous material culture.

Palo Verde (*Parkinsonia florida, P. microphylla*)

The Blue and Foothill Palo Verde are leguminous trees native to the Sonoran Desert and widely distributed across central and southern Arizona. The seeds were a food source for several Indigenous groups, including the Pima, Tohono O'odham, Cocopa, Mohave, Yuma, and Cahuilla, who processed them in different ways to reduce bitterness and increase digestibility. The Pima ate the beans, peas, and seeds raw or boiled, while the Tohono O'odham winnowed, parched, and sun-dried the beans for long-term use as a staple food [3]. The Cocopa roasted the seeds and ground them into mush [1,3]. The Mohave and Yuma parched seeds until nearly burned and consumed them during periods of food scarcity [3]. The wood also had utilitarian value. The Pima carved large branches into ladles and cooking utensils [4], and the Cahuilla used mature trees as temporary shade structures while camping [5].

In addition to human use, the Foothill Palo Verde produces nectar, seeds, and shaded cover that support a wide range of desert wildlife. It is especially important to pollinators and small mammals, including insects, rodents, and granivorous birds [1,2].

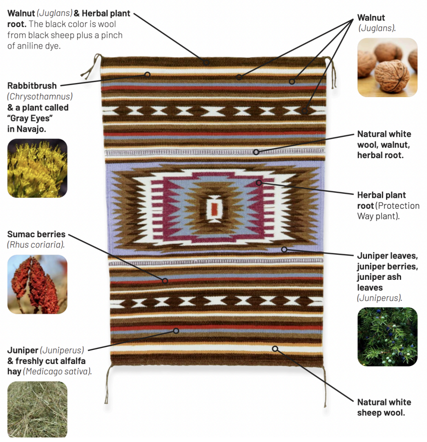
Alligator Juniper (*Juniperus deppeana*)

Alligator Juniper is a mid-elevation conifer identifiable by its blocky, scale-like bark. It has been widely used by Indigenous communities for its edible berries, durable wood, bark, and ceremonial significance.

The cone berries were widely consumed. The Yavapai gathered fallen berries, crushed them in bedrock mortars, soaked them in water, and sucked out the juice [8]. They also prepared cakes with pressed berries stored in baskets and made beverages from the meal [9]. The Apache boiled berries for food, and the Ramah Navajo ate them raw or ground [9]. The Zuni flavored foods such as blood sausage and cornbread with the berries [10]. Among the Hopi, juniper gum was also chewed like resin candy [7].

The wood and bark were used extensively for construction, fuel, and household items. The Zuni and Havasupai fashioned shredded bark into torches, mats, fire carriers ("slow matches"), and padding for baskets, cradleboards, and bedding [7,11]. Archaeological evidence from the Grand Canyon region also shows juniper bark was used in sandals, adobe insulation, and pit-house construction [7].

Juniper also held medicinal value. Among the Yavapai, warm decoctions of roasted juniper twigs were given to women postpartum to encourage recovery [8]. The Havasupai used bark torches to prevent rheumatism and believed the smoke could improve memory [8]. At Hopi and Zuni pueblos, juniper bark was used for dental care and wound sealing [8]. Ceremonially, juniper branches appeared in Hopi kachina dances, Zuni New Year fire rituals, and Navajo healing ceremonies. Among the Navajo, juniper branches featured in healing dances, burial rituals, and Yeibichai performances, where they symbolically expelled illness or spiritual harm [8].


Walnut (Juglans) & Herbal plant root. The black color is wool from black sheep plus a pinch of aniline dye.
Rabbitbrush (Chrysothamnus) & a plant called "Gray Eyes" in Navajo.
Sumac berries (Rhus coriaria).
Juniper (Juniperus) & freshly cut alfalfa hay (Medicago sativa).
Walnut (Juglans).
Natural white wool, walnut, herbal root.
Herbal plant root (Protection Way plant).
Juniper leaves, juniper berries, juniper ash leaves (Juniperus).
Natural white sheep wool.

Arizona Walnut (*Juglans major*)

Arizona Walnut is native to canyons and streambeds across Arizona. Indigenous groups used it primarily for its nutrient-rich nuts and practical applications in construction and dyeing.

The nuts were an important seasonal and stored food for the Chiricahua and Mescalero Apache, Yavapai, Hualapai, and Navajo. They were eaten directly or combined with other desert foods such as mesquite syrup, mescal, or sotol to make energy-dense pastes and drinks. The Yavapai pulverized the nut meat in mescal syrup or soaked crushed nuts in water to prepare beverages [11]. Nuts were often stored for winter use by the Yavapai and Apache [11,12].

Beyond culinary uses, the Mescalero Apache harvested trees to build temporary dome-shaped lodges while away from permanent settlements [12]. Additionally, walnut husks contain juglone, a natural tannin that binds well to fibers to dye clothing and crafts. The Apache soaked the shells to produce a black paint for decorative purposes [12]. The Navajo and Hualapai boiled walnut shells to make brown dye, commonly used to stain wool, hides, and other materials [11,12].

Velvet Mesquite (*Neltuma velutina*)

Velvet Mesquite is native to desert washes and lowland areas of central and southern Arizona. It’s pods were a staple seasonal food for the Pima, Tohono O’odham, Maricopa, and Cocopa. They were eaten raw or more often dried, parched, and ground into flour for bread, dumplings, and drinks [14,16]. The Pima mixed pounded beans with water to make a sweet beverage, while others used the flour to sweeten gruels [16]. Pods and seeds were commonly stored for winter, and gum exudates were chewed, boiled into preserves, or combined with saguaro syrup to make jam [14].

Mesquite also had broad medicinal applications. The Pima and Tohono O’odham used gum, leaves, bark, and beans in treatments for burns, infections, pink eye, gastrointestinal issues, headaches, and postpartum care [14–16]. Gum was applied to cracked skin, newborn navels, and wounds. Additionally, leaf infusions were used to treat stomach and eye ailments, and bark decoctions served as both topical and internal remedies [14,16].

Its wood and roots supported essential material needs. The Tohono O’odham used mesquite in basketry, housing frames, and fencing. Green twigs served as cooking tools, and branches were carved into weeding tools [14]. Among the Pima, gum mixed with black clay was used as a black hair dye [15].

Arizona Cypress (*Hesperocyparis arizonica*)

Arizona Cypress is a drought-tolerant conifer native to canyons and foothills in central and southeastern Arizona. Despite its prevalence, there is limited ethnobotanical documentation specific to this species due to its historical taxonomic confusion with junipers (*Juniperus spp.*) and other cypress species [17]. What is known is largely inferred from uses of related species. The Kawaiisu of California, for example, used cypress seeds and cones in medicinal infusions to treat chest pain, coughs, kidney conditions, menstrual issues, and musculoskeletal ailments [18,19].

References:

1. Walters, J. E., & Backhaus, B. (1992). Shade and Color with Water-Conserving Plants. Portland, OR: Timber Press.
2. Southwest Desert Flora. (n.d.). Parkinsonia microphylla (Yellow Paloverde). Retrieved May 15, 2025, from https://southwestdesertflora.com/WebsiteFolders/All_Species/Fabaceae/Parkinsonia%20microphylla,%20Yellow%20Paloverde.html
3. Native American Ethnobotany Database. (n.d.). Parkinsonia microphylla / Parkinsonia florida. University of Michigan-Dearborn. Retrieved May 15, 2025, from http://naeb.brit.org/uses/search/?string=Parkinsonia
4. Curtin, L. S. M. (1949). By the Prophet of the Earth. Santa Fe: San Vicente Foundation, p. 90.
5. Bean, L. J., & Saubel, K. S. (1972). Temalpakh (From the Earth): Cahuilla Indian Knowledge and Usage of Plants. Banning, CA: Malki Museum Press, p. 52.
6. U.S. Forest Service. (n.d.). *Juniperus deppeana*. Fire Effects Information System. Retrieved from https://www.fs.usda.gov/database/feis/plants/tree/jundep/all.html
7. McHenry, D. E. (1934). “The Indian Use of Juniper.” *Grand Canyon Nature Notes*, Vol. 9, No. 1. National Park Service. https://npshistory.com/nature_notes/grca/vol9-1c.htm
8. Native American Ethnobotany Database. (n.d.). *Juniperus deppeana*. University of Michigan-Dearborn. Retrieved from http://naeb.brit.org/uses/search/?string=Juniperus+deppeana
9. Miller, R. K., & Albert, S. K. (1993). Zuni cultural relationships to pinon-juniper woodlands. In Aldon, E. F., & Shaw, D. W. (Eds.), *Managing pinon-juniper ecosystems for sustainability and social needs*. Gen. Tech. Rep. RM-236. USDA Forest Service, Rocky Mountain Research Station, pp. 74–78.
10. Spier, L. (1928). *Havasupai Ethnography*. Anthropological Papers of the American Museum of Natural History, Vol. 29, Part 3.
11. Native American Ethnobotany Database. (n.d.). Juglans major (Arizona Walnut). University of Michigan-Dearborn. Retrieved May 15, 2025, from http://naeb.brit.org/uses/species/2033/
12. Southwest Desert Flora. (n.d.). Juglans major (Arizona Walnut). Retrieved May 15, 2025, from https://southwestdesertflora.com/WebsiteFolders/All_Species/Juglandaceae/Juglans%20major,%20Arizona%20Walnut.html
13. Manuel, D. (2020). Mesquite Usage by the O’odham and Piipaash. O'Odham Action News. Salt River Pima-Maricopa Indian Community. https://oan.srpmic-nsn.gov/mesquite-usage-by-the-oodham-and-piipaash/
14. Native American Ethnobotany Database. (n.d.). Prosopis velutina (Velvet Mesquite). University of Michigan-Dearborn. Retrieved May 15, 2025, from http://naeb.brit.org/uses/search/?string=prosopis+velutina
15. Southwest Desert Flora. (n.d.). Prosopis velutina (Velvet Mesquite). Retrieved May 15, 2025, from https://southwestdesertflora.com/WebsiteFolders/All_Species/Fabaceae/Prosopis%20velutina,%20Velvet%20Mesquite.html
16. USDA NRCS & UC Davis Arboretum. (2000). Prosopis velutina – Velvet Mesquite Plant Guide. Retrieved May 15, 2025, from https://plants.usda.gov
17. USDA NRCS. (2006). Plant Guide: Hesperocyparis arizonica (Arizona Cypress). Retrieved May 15, 2025, from https://plants.usda.gov/DocumentLibrary/plantguide/pdf/pg_hear22.pdf
18. Native American Ethnobotany Database. (n.d.). Cupressus arizonica. University of Michigan-Dearborn. Retrieved May 15, 2025, from http://naeb.brit.org/uses/search/?string=Cupressus+arizonica
19. Southwest Desert Flora. (n.d.). Cupressus arizonica (Arizona Cypress). Retrieved May 15, 2025, from https://southwestdesertflora.com/WebsiteFolders/All_Species/Cupressaceae/Cupressus%20arizonica,%20Arizona%20Cypress.html

Image Links:

1. Palo Verde: https://tucsoncleanandbeautiful.org/product/foothills-palo-verde/
2. Alligator Juniper: https://southwestdesertflora.com/WebsiteFolders/All_Species/Cupressaceae/Juniperus%20deppeana,%20Alligator%20Juniper.html
3. Arizona Walnut: https://www.ohio.edu/sites/default/files/sites/museum-complex/files/VegetalDyes.pdf
4. Velvet Mesquite: https://tucsoncleanandbeautiful.org/wp-content/uploads/2023/12/Screenshot-2025-01-03-at-5.51.38%E2%80%AFPM.png

Fossils of the Petrified Forest

Anwesha Das

The Petrified Forest contains animal and plant fossils from the Triassic period (about 200 million years ago), which was marked by the era of dinosaurs and giant forests. Fossils allow a window into the past to study and learn more about the flora and fauna from a given period. In this report, I am going to focus on fossils of **Ginkgo trees, bee nests, Postosuchus, and Ceratopsidae**.

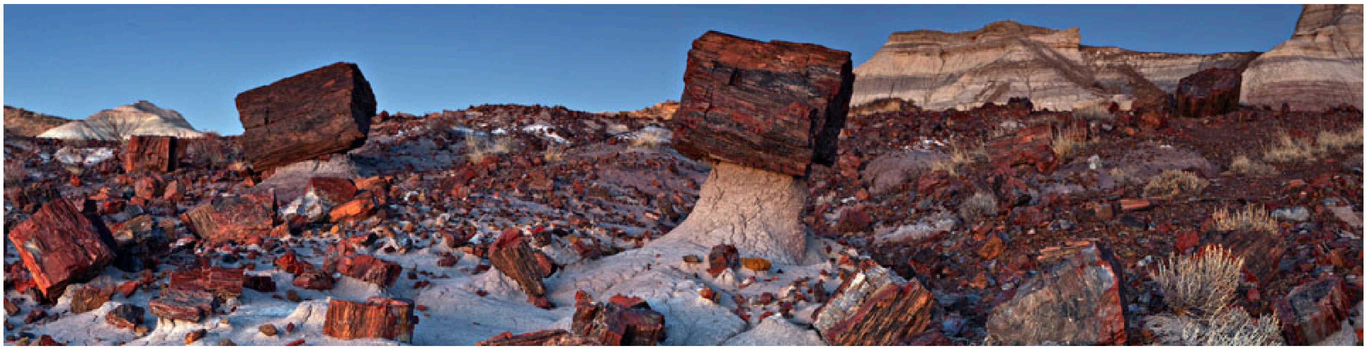


Figure 1: Petrified Forest (Arizona)

Ginkgo

The Gingko (*Ginkgo biloba*) is part of an ancient class of plants (Ginkgoales). While Ginkgo biloba is the only species found today, it is believed that several others have gone extinct. The oldest fossil record from this plant family is from 220 million years ago, from the late Triassic period. A new extinct species (*Ginkgoites watsoniae*) was uncovered in the Petrified Forest in Arizona not long ago, in the green mudstones of the Blue Mesa Member of the Chinle Formation.

The Gingko tree is native to East Asia and has fan-shaped leaves that turn yellow during the Fall. They grow to become large trees (50-80 ft tall). From the shape of the fossils, it is believed that the extinct species of Gingko plants had similar characteristics.

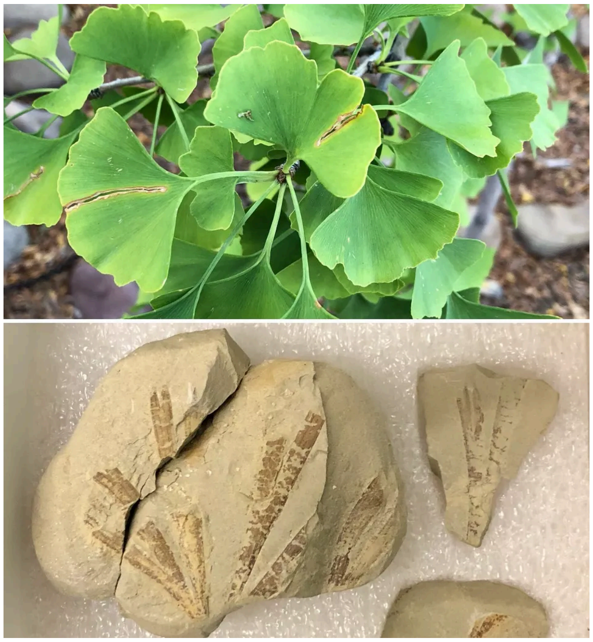


Figure 2: Living Ginkgo biloba and fossils of Ginkgoites watsoniae

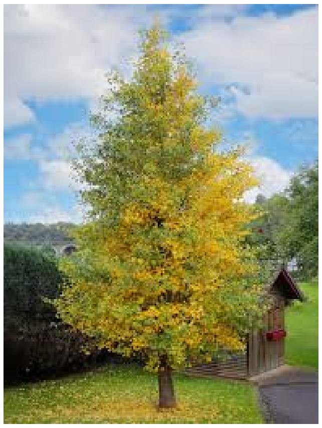
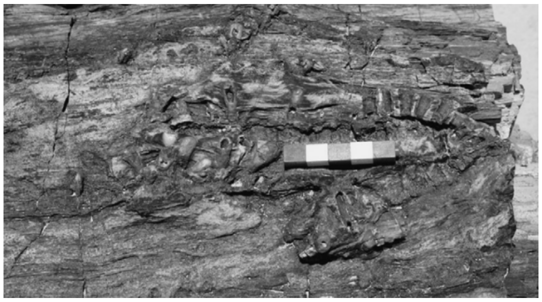


Figure 3: Ginkgo tree

Bee Nests

Trace fossils, believed to be bee nests, were found in the Chinle Formation, the same location where the Ginkgo fossils were found. Colonial bees' nests were described as being found in silicified wood of the Late Triassic Age, from about 200 million years ago. It is believed that two types of bees' nests were found – those in the fossilized petrified wood and those in the soil. These nests are believed to have complex structures with rows of cells, which are lined with plant



materials and bee secretion. Several studies have described and studied these wasp and bee nests, claiming that they are identical in size, shape, and micro-physiology to nests of extinct social bees. Additionally, chemical analysis of the linings of such cells revealed a phylogenetic link to modern bees. However, these claims have been met with criticism, claiming that they lack important features such as cells with smooth linings and spiral closure caps, and instead claim that such borings may be arthropod-generated (such as beetles).

Postosuchus

Postosuchus were "dinosaur-like" archosaurs ('rauisuchid') that preyed on small Triassic dinosaurs and were the largest carnivores during this period, standing at about 10-13ft long. Modern crocodiles are from the lineage of archosaurs. In 1932, a paleontologist collected over a hundred 'rauisuchid' bones that are believed to be from seven different individuals from the Petrified Forest, which were later assigned to *Postosuchus kirkpatricki.* Postosuchus's skeleton and remains have been thoroughly studied.

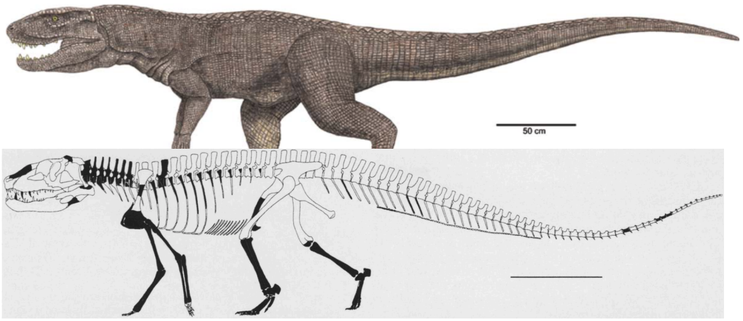


Figure 5: Reconstruction from preserved bones

Ceolophysis

Coelophysis sp. (Coelophysoidea) were dinosaurs found in the Petrified Forest in the Triassic Period, the dawn of the dinosaurs. Bipedal, carnivorous dinosaurs, no larger than humans, were found in this area and were some of the earliest known dinosaurs. In 1947, a paleontologist led a field study for a year in search of dinosaur fossils/ remains in the Ghost Ranch Area, including the Petrified Forest, which led to the discovery of full skeletons of several small theropods. Their remains have been well studied and preserved.

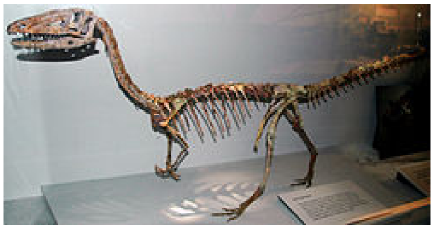


Figure 6: Skeleton of a Coelophysis

References:

1. A Catalog of Upper Triassic Plant Megafossils of the Western United States Through 1988 (Sidney Ash, 1989)
2. Dinosaurs. National Parks Service. Available at: https://www.nps.gov/pefo/learn/nature/dinosaurs.htm (Accessed: 25 May 2025).
3. Ginkgo biloba. National Parks Service. Available at: https://www.nps.gov/pefo/learn/nature/ginkgo-biloba.htm (Accessed: 25 May 2025).
4. Ginkgo (2025) Encyclopædia Britannica. Available at: https://www.britannica.com/plant/ginkgo-tree (Accessed: 25 May 2025).
5. Hasiotis, S. et al. (1998) 'Research update on hymenopteran nests and cocoons, Upper Triassic Chinle Formation, Petrified Forest National Park, Arizona', Palaeogeography, Palaeoclimatology, Palaeoecology, 286(3–4).
6. Lucas, S.G., Minter, N.J. and Hunt, A.P. (2010) 'Re-evaluation of alleged bees' nests from the Upper Triassic of Arizona', Palaeogeography, Palaeoclimatology, Palaeoecology, 286(3–4), pp. 194–201. doi:10.1016/j.palaeo.2010.01.010.
7. Lucas, S.G. and Heckert, A.B. (2000) Coelophysis bauri and syntarur rhodesiensis compared, with comment on the preparation and preservation of fossils from the ghost ranch Coelophysis quarry.
8. Park Archives: Petrified Forest National Park. Available at: https://npshistory.com/publications/pefo/index.htm (Accessed: 25 May 2025).
9. Postcranial skeleton of Postosuchus kirkpatricki (Archosauria: Paracrocodylomorpha), from the Upper Triassic of the United States
10. Peyer, K. et al. (2008) 'A new suchian archosaur from the Upper Triassic of North Carolina', Journal of Vertebrate Paleontology, 28(2), pp. 363–381. doi:10.1671/0272-4634(2008)28

Ting-Juan Liao

Desert Farming: Indigenous vs Modern

1. Do we farm in the desert?

Water and rich soil are essential in farming, which desert has neither of them. However, many civilizations actually developed from desert, such as ancient Assyria, Ancient Egypt, and the Indus Valley Civilization. All these civilizations were founded in irrigated regions surrounded by desert. How did these civilizations survive in drawn area? In modern days, Arizona, state known for its desert climate has $23 billion farming industry, and 35% of land is farmland. Yes, we did and still farm in desert, but how did people make this happen?

2. Crops

2.1 Crops grow in dry climate

People grow the crops that required less water and easy to survived in thirsty. For example, cotton is a common plant in desert like Arizona for centuries. Nowadays, Arizona is still famous for planting high quality cotton.

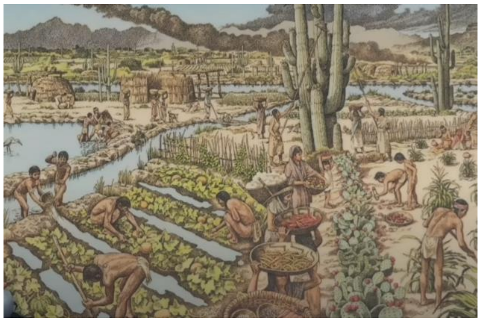


Figure 1. Imagination of people farming with canals.

2.2 Holistic systems

Different plants complements each other and the environment around it. Beans provide nitrogen to the soil; Corn supply sticks for beans to grow upon; Leaves from the squash provide ground cover protection keeping soil moisture.

3. Technology and Methods

3.1 Construction

3.1.1 Canals

In 1600, people in Arizona use canals to leads water from the river to their tribe to grow crops and cotton.

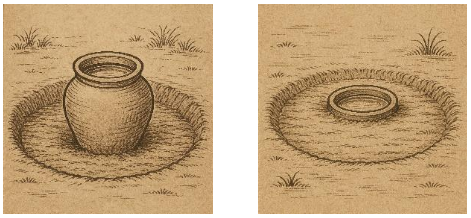


Figure 2. Schematic diagram of drip irrigation based on my understanding of the description in the book, generate by ChatGPT.

3.1.2 Rock Dams

By slowing down the flow of water, rock dams allow the water to pool behind the dam. This helps to recharge groundwater, leading to increased water availability for vegetation and local communities.

3.2 Drip Irrigation

Drop irrigation is a way to save water and nutrients while farming. The earliest drop irrigation could track back between 8 B.C. to 32 B.C. in “氾勝之書”. The modern drip irrigation was development in Germany in 1860. Modern drip irrigation began its development in Germany in 1860. By dripping water slowly to the roots of plants could minimize evaporation. This can achieve by either dripping above the soil surface or buried the pipe below the surface.

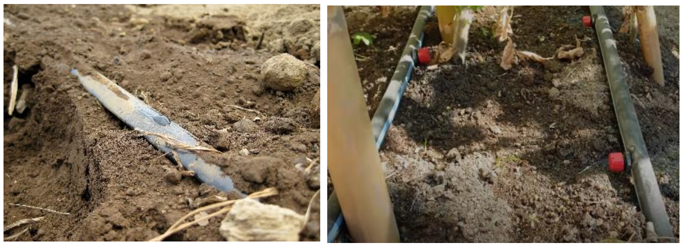


Figure 3. Different ways of drip irrigation. Left: drip tape; Right: Plastic emitter

3.3 Garden design

3.3.1 Sunken Beds

Sunken beds are dug down several inches, allowing irrigation water to slowly sink in rather than run off and keep soil and roots cooler during hot seasons. Figure 5 demonstrates steps to build sunken beds. First, remove all the weeds; Then, dig out beds and add compost. Last, create pathways between beds.

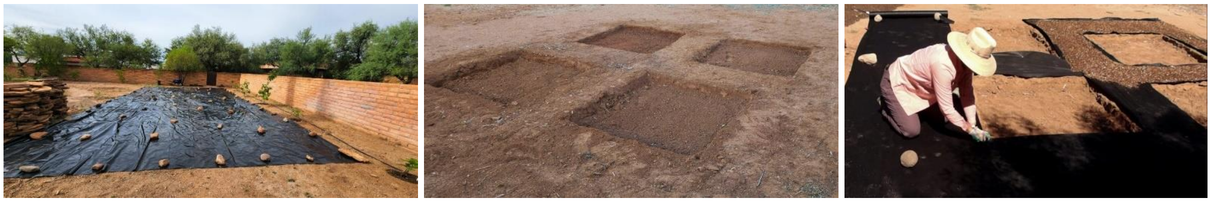


Figure 4. From left to right: steps for making sunken beds.

3.3.2 Keyhole gardens

Keyhole gardens allow gardener deposit vegetable scraps into the basket. Then, plants around could get nutrients from it. Also, the stones around it could help with trapping moisture within the bed.

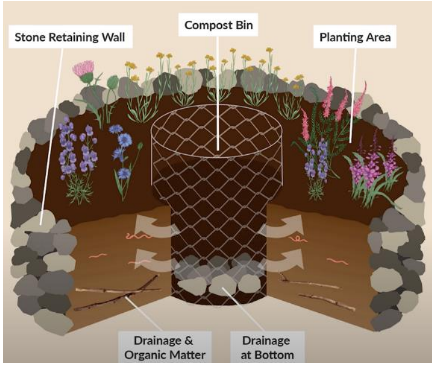


Figure 5. Keyhole garden.

Reference:

- How He Turned Desert Sand Into Fertile Farm Land In 3 Months!: https://www.youtube.com/watch?v=cc3-3s115mM.
- How This Woman Turned Arizona's Desert into a Farmland Oasis: How This Woman Turned Arizona's Desert into a Farmland Oasis - YouTube
- 氾勝之 (8 B.C to 32 B.C.) 氾勝之書
- R. Goyal, Megh (2012). Management of drip/trickle or micro irrigation. Oakville, California: Apple Academic Press. p. 104. ISBN 978-1-926895-12-3
- Degani, Corin (2023). "How Israel achieved one of the most secure water economies, drip by drip". Haaretz.
- Growing In The Garden and Judd, A. (2025) Sunken garden beds: Water-wise gardening in the Desert, Growing In The Garden. Available at: https://growinginthegarden.com/sunken-garden-beds-water-wise-gardening-in-the-desert/ (Accessed: 19 May 2025).
- Napa Master Gardener Column (2021) https://ucanr.edu/blog/napa-master-gardener-column/article/garden-gold
- How Arizona Turns Desert Into Fertile Farmland For Local Community!: https://www.youtube.com/watch?v=b_9vzTo-8a0

Can you have your [yellow]cake and eat it too? Uranium mining at Pinyon Plain

Kian Faizi

Just southeast of Tusayan, AZ, less than 10 miles south of the Grand Canyon and in a clearing inside the Kaibab National Forest, lies the Pinyon Plain uranium mine. First established in the 1980s as Canyon Uranium Mine, it never became operational due to crashing ore prices; instead, the project sat dormant for decades while the claim was bought and sold multiple times, eventually being acquired by Energy Fuels Inc (EFI). In recent years, changing markets and a renewed interest in bolstering America's energy independence have led the mine to become viable again — and thus, as of last year, finally active. But can this place truly ever be the heart of our domestic nuclear energy program? (No.) And is it worth the potential cost to the people, flora, and fauna that live here? (Also no.)

From the surface, the mine has a surprisingly small footprint of around 15 acres. This is because all of the action happens in a compact, semicylindrical deposit (perhaps only 100 meters in diameter) lying vertically underground known as a breccia pipe. These chimney-like structures are thought to form in a multiple ways, like via hydrothermal incursions on fractured rock, or the collapse of limestone; this particular one is enriched in uranium oxides that make it ostensibly attractive to mine. (**1**) To access it, workers sunk a parallel vertical shaft by drilling and blasting through rock to a depth of 450 meters, then lifting out the debris with the steel headframe and hoist, which are the most striking features of the mine visible aboveground.

However, the ground here is also host to complex hydrology, including two major aquifers: the Coconino and the Redwall-Muav (**Figure 1**). The latter connects to the Grand Canyon itself, including the famous Havasu Springs which are a major tourist destination as well as the literal lifeline (e.g. drinking water source!) of the Havasupai tribe, whose name means "People of the Blue-Green Water". Hence the foremost environmental concern associated with Pinyon Plain is the possibility of serious groundwater contamination, with the potential to poison native peoples, destroy a major tourist site, and harm endemic flora and fauna.

Is this legit? EFI thinks not; one spokesman described the mine as "low impact with zero risk to groundwater". (**2**) And yet in 2016, workers breached the Coconino, flooding the shaft with groundwater. Since then, approximately 2 million gallons of water have been pumped out of the mine each month (totalling over 67 million gallons thus far); as a result of coming into contact with the mine, this water is known to have elevated levels of arsenic, lead, and uranium. (**3**) Although the Redwall-Muav lies hundreds of feet deeper than the lowest point in the mineshaft, should we really believe that it is insulated by hydrologically impenetrable rock — especially if the potential risks to life and environment are so great?

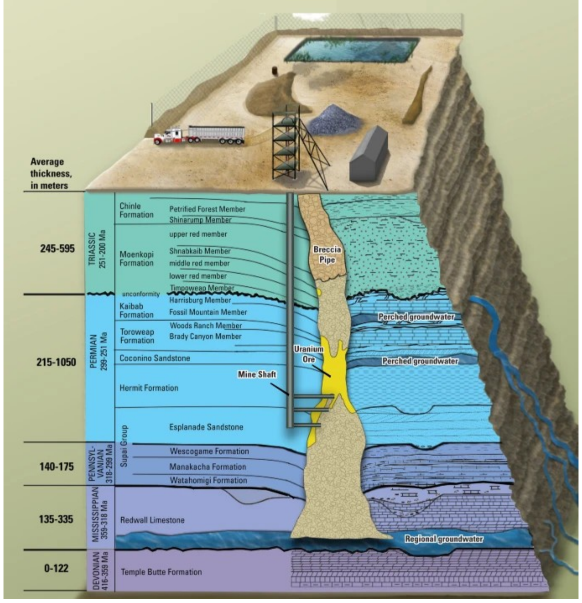

Average thickness, in meters
245-595
215-1050
140-175
135-335
0-122
TRIASSIC 251-200 Ma
PERMIAN 299-251 Ma
PENNSYLVANIAN 318-299 Ma
MISSISSIPPIAN 359-318 Ma
DEVONIAN 416-359 Ma
Supai Group
Chinle Formation
Petrified Forest Member
Shinarump Member
upper red member
Moenkopi Formation
Shnabkaib Member
middle red member
lower red member
Timpoweap Member
unconformity
Harrisburg Member
Kaibab Formation
Fossil Mountain Member
Woods Ranch Member
Toroweap Formation
Brady Canyon Member
Coconino Sandstone
Hermit Formation
Esplanade Sandstone
Wescogame Formation
Manakacha Formation
Watahomigi Formation
Redwall Limestone
Temple Butte Formation
Breccia Pipe
Uranium Ore
Mine Shaft
Perched groundwater
Perched groundwater
Regional groundwater

Figure 1: Schematic of a breccia pipe uranium mine like the one at Pinyon Plain; note the complex hydrology of the site. (Source: Tillman et al., 2021)

Nonetheless, business continues to ramp up at Pinyon Plain, which extracted its first uranium ore on January 8, 2024. (**4**) Each day, broken ore is hoisted to the surface and loaded onto trucks, which then drive approximately 300 miles to White Mesa, UT for processing (**Figure 2**). (Ore transportation was paused for 6 months due to a dispute with the Navajo Nation, who own some of the roads along the trucking route, but resumed after mutual agreement on February 12, 2025.) Waste rock is backfilled into the mine where possible to minimize surface tailings (waste) and reduce the risk of subsidence. And all that Coconino water — around 7,000 gallons per day — has to be pumped out 24/7 and deposited into a lined sump pond on the surface for evaporation. Alongside other agenices, the Arizona Department of Environmental Quality (AZDEQ) publishes quarterly reports of Pinyon Plain's water quality compliance. The most recent data from Q1 2025 show elevated contaminant concentrations, and also that some portion of this water is "treated" onsite and mist-sprayed under the auspices of suppressing dust (while raising new concerns about potentially aerosolizing harmful products). (**5**)

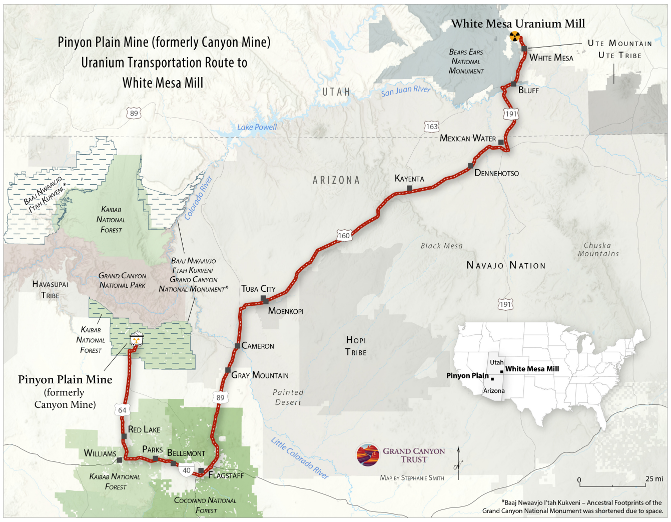

Pinyon Plain Mine (formerly Canyon Mine)
Uranium Transportation Route to
White Mesa Mill
White Mesa Uranium Mill
Bears Ears National Monument
White Mesa
Ute Mountain Ute Tribe
Utah
San Juan River
Bluff
89
Lake Powell
163
191
Mexican Water
Dennehotso
Arizona
Kayenta
Baaj Nwaavjo I'tah Kukveni*
Kaibab National Forest
Colorado River
160
Black Mesa
Chuska Mountains
Navajo Nation
Baaj Nwaavjo I'tah Kukveni Grand Canyon National Monument*
Havasupai Tribe
Grand Canyon National Park
Tuba City
Moenkopi
191
Kaibab National Forest
Cameron
Hopi Tribe
Utah
White Mesa Mill
Pinyon Plain
Arizona
Gray Mountain
Pinyon Plain Mine (formerly Canyon Mine)
Painted Desert
89
64
Red Lake
Williams
Parks
Bellemont
40
Flagstaff
Little Colorado River
Grand Canyon Trust
Map by Stephanie Smith
0
25 mi
Kaibab National Forest
Coconino National Forest
*Baaj Nwaavjo I'tah Kukveni – Ancestral Footprints of the Grand Canyon National Monument was shortened due to space.

Figure 2: Map of the ore trucking route from Pinyon Plain to White Mesa. (Source: Grand Canyon Trust)

Still, one can argue that all the data really show is that nothing truly catastrophic has yet transpired at Pinyon Plain. And perhaps nothing will! After all, this is "the highest-grade uranium mine in the U.S.", with a proven reserve of around 1 million pounds of uranium. (**6**) (The "grade" refers to the fraction of the ore that is yellowcake U_3O_8; at Pinyon Plain, it's around 0.6-0.9%.) Surely we need this, so we can ditch all of that sketchy commie ore we have to import? Yet in 2023, the US Energy Information Administration reported that three-quarters of our uranium came from Canada, Australia, and Kazakhistan, with just 12% from Russia and 5% from domestic sources — for a total equivalent to some 50 million pounds of U_3O_8. (**7**) That is to say, we're tearing up sacred indigenous lands on the edge of the Grand Canyon just for the possibility of making a few paltry percent of our annual uranium demand. Is that really the best we can do?

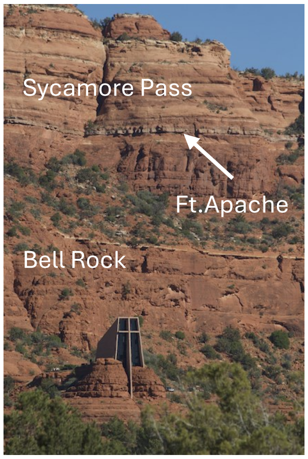
Once the Pinyon Plain deposit has been exhausted (which should take less than a decade at current rates), mining may stop — but the environmental impacts will not. First, all surface structures will be removed. The shaft itself will be backfilled to keep it from accumulating groundwater in contact with the breccia pipe. Once all sump pond water has evaporated, the leftover sludge (which will be enriched in heavy metals and radionuclides) must be transported to a dedicated tailings facility. In the long term, diligent post-closure monitoring of the water table is essential to protect the wellbeing of those whose lives depend on the nearby aquifers. The bold assumption is that EFI remains solvent long enough to cover all of these costs, until finally the land can be returned to the stewardship of the Forest Service. In the truest sense, then, remediation means an unlikely, decades-long promise of holistic care for the Pinyon Plain site.

References

1. https://en.wikipedia.org/wiki/Breccia_pipe
2. https://apnews.com/article/uranium-mine-grand-canyon-nuclear-power-98d43974de13924fb3c36f62b55f53b3
3. https://www.grandcanyontrust.org/resources/canyon-mine-pinyon-plain-uranium-mine-water-dashboard/
4. https://www.fs.usda.gov/r03/kaibab/forest-products/nonwood-products/pinyon-plain-mine-formerly-canyon-uranium-mine
5. https://azdeq.gov/WQD/PinyonPlainMine
6. https://www.energyfuels.com/pinyon-plain-mine/
7. https://www.eia.gov/uranium/marketing/

Schnebly Hill Formation

Eran Funaro


Sycamore Pass
Ft.Apache
Bell Rock

The Permian (286–273 Ma) Schnebly Hill formation constitutes the upper part of the Supai group in the Sedona area, and its thick (800-100 ft) red sandstone walls are a major contributor to its unique landscape. The formation is made up of three sections; the Bell Rock sandstone member, the Fort Apache limestone member, and the Sycamore Pass sandstone member. This layer is separated from the Hermit formation by an unconformity of less than a million years.

The sandstones of the Schnebly Hill formation are a bit odd, they are flat bedded and intercalated with fine limestone conglomerate layers indicating submerged deposition, yet individual sand grains are eroded in eolian fashion pointing at wind-based transport.

As Earth's continents were beginning to assemble into the supercontinent Pangaea around 280 million years ago, the future Sedona area lay on the arid, western edge of this giant landmass. Rivers caried sandy sediment from the Appalachians to broad floodplains in modern day Montana and Wyoming where the river water was lost to evaporation ground seepage. From these dry riverbeds and flood plains northern winds carried sand grains to the south toward northern Arizona. Low-slung coastal dunes developed and stretched for miles in all directions. In these settings the red rocks of Sedona were deposited.

Pedregosa Sea - To the south in southeastern Arizona, coeval limestone mark the location of the warm, shallow Pedregosa sea. Land subsidence of the Sedona area alongside eustatic shifts through time , drove a northern sea expansion that gradually inundated the Sedona area. The wide-ranging and shifting tides along the migrating shorelines washed over and flattened the coastal dunes into horizontal layers of the Bell Rock Member of the Schnebly Hill Formation. Seawater rose higher and eventually covered the area for a short period, leaving a layer of limestone in its wake. The gray Fort Apache Member (10-20 ft) of the Schnebly Hill Formation is sandwiched between thick layers of red sandstone.

As the seaway retracted southeast, coastal dunes crept back into the area from the northwest, and deposited the Sycamore Pass Member of the Schnebly Hill Formation. The land kept subsiding under the incoming sand load progressively burying and preserving the dunes. as the shoreline drew back hundreds of miles away inland dunes rather than coastal dunes became dominant and marked the shift to the Coconino Sandstone that overlies Schnebly Hill.

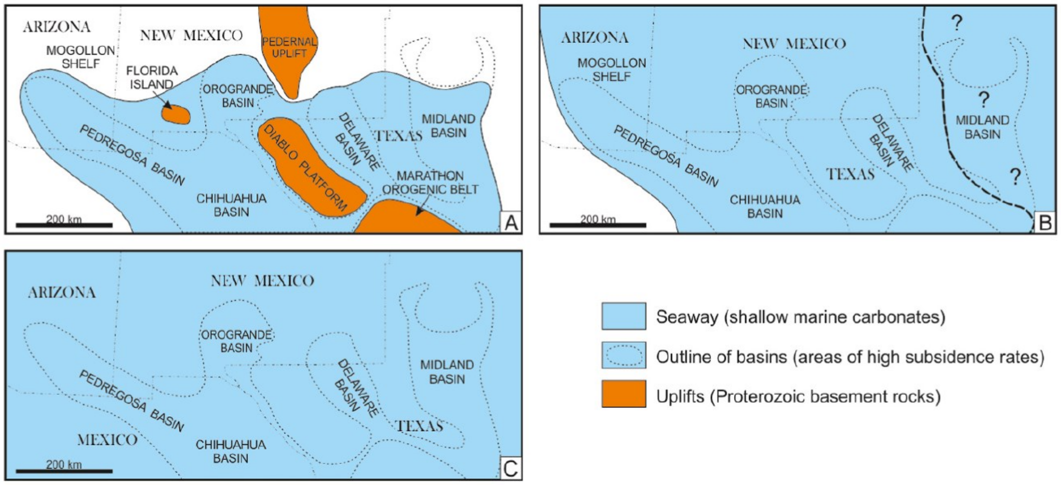

ARIZONA
NEW MEXICO
MOGOLLON SHELF
FLORIDA ISLAND
PEDERNAL UPLIFT
OROGRANDE BASIN
DELAWARE BASIN
TEXAS
MIDLAND BASIN
PEDREGOSA BASIN
DIABLO PLATFORM
MARATHON OROGENIC BELT
CHIHUAHUA BASIN
200 km
A
ARIZONA
NEW MEXICO
MOGOLLON SHELF
OROGRANDE BASIN
DELAWARE BASIN
?
?
MIDLAND BASIN
?
PEDREGOSA BASIN
TEXAS
CHIHUAHUA BASIN
200 km
B
ARIZONA
NEW MEXICO
OROGRANDE BASIN
DELAWARE BASIN
MIDLAND BASIN
PEDREGOSA BASIN
TEXAS
MEXICO
CHIHUAHUA BASIN
200 km
C
Seaway (shallow marine carbonates)
Outline of basins (areas of high subsidence rates)
Uplifts (Proterozoic basement rocks)

Fig. 19. Maps of the three Early Permian seaways in the American Southwest. A, Wolfcampian. B, Early Leonardian. C, Late Leonardian.

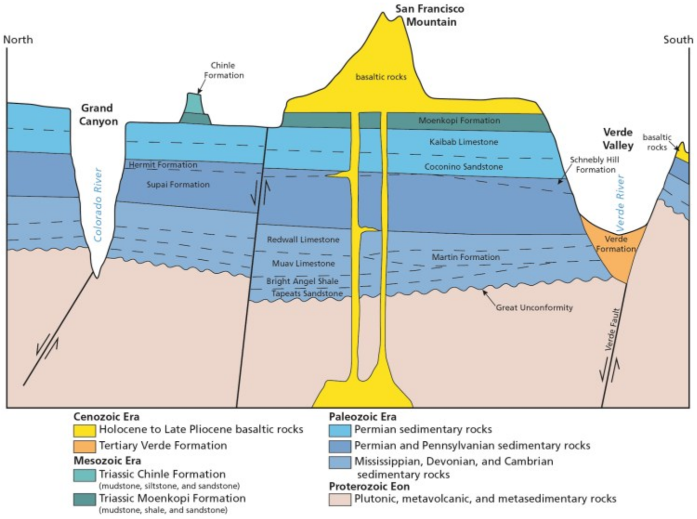
Nobody expects the Spanish inquisition or a north-east seaway transgression. Nevertheless, between 275-270 million years ago, that is exactly what happened (the latter). At first, salty mudflats deposited the Toroweap formation and as this sea expanded eastward it left another limestone layer, called the Kaibab Formation. This is the rock layer that caps much of northern Arizona, including the Mogollon Rim and the Grand Canyon.

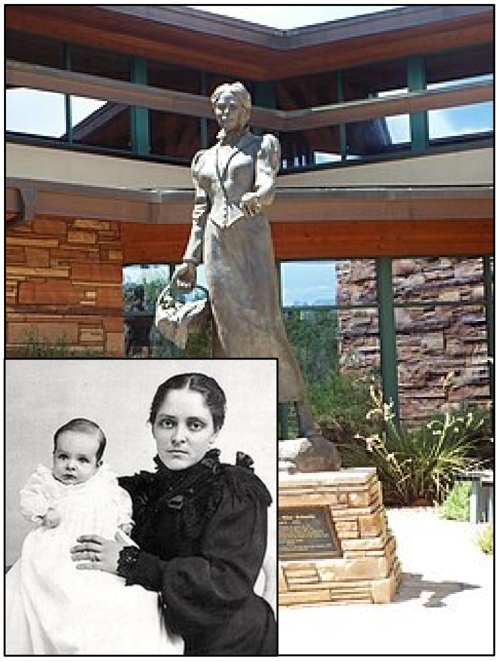
More recent

25 - 30 ma - the Mogollon rim formed by erosion cutting the Colorado plateau to our north while to the south, central and southern Arizona had been uplifted in a mountain range that called the Mogollon Highlands. Tilting the red rocks in the Sedona area. Soon thereafter the sandstones were exposed by erosion. An early version of the Verde Valley formed between the uplifted terrain to the south and the newly formed Rim.

15 ma, volcanism commenced just south of Sedona with outpourings of voluminous basalt lava.

The Verde fault near Jerome further depressed the Verde Valley such that the Verde River became ponded into a freshwater lake. This lake stretched nearly 35 miles from below Camp Verde to Clarkdale and from Jerome to Sedona.


San Francisco Mountain
North
South
Chinle Formation
basaltic rocks
Grand Canyon
Moenkopi Formation
Kaibab Limestone
Verde Valley
basaltic rocks
Hermit Formation
Coconino Sandstone
Schnebly Hill Formation
Supai Formation
Colorado River
Verde River
Redwall Limestone
Verde Formation
Martin Formation
Muav Limestone
Bright Angel Shale
Tapeats Sandstone
Great Unconformity
Verde Fault
Cenozoic Era
Holocene to Late Pliocene basaltic rocks
Tertiary Verde Formation
Mesozoic Era
Triassic Chinle Formation (mudstone, siltstone, and sandstone)
Triassic Moenkopi Formation (mudstone, shale, and sandstone)
Paleozoic Era
Permian sedimentary rocks
Permian and Pennsylvanian sedimentary rocks
Mississippian, Devonian, and Cambrian sedimentary rocks
Proterozoic Eon
Plutonic, metavolcanic, and metasedimentary rocks



Naming

Sedona Schnebly (born Sedona Arabella Miller February 24, 1877 – November 13, 1950) was an early pioneer in the Oak Creek area of Arizona. She was the namesake of the town of Sedona, Arizona. She helped in the establishment of the family farm and general store in the town. She also served as the town's school teacher. Sedona saved funds to build the Wayside Chapel. Among her legacy is a sculpture of a statue in her likeness by the Sedona Red Rocks Arts Council honoring her memory.

The Schneblys believed that the fast-growing community needed a post office. T.C. wanted to be the area's first postmaster and so wrote to the Postmaster General in Washington, D.C., suggesting "Oak Creek Crossing" and "Schnebly Station" as town names. Both were rejected as too long. Ellsworth, Theodore's brother, suggested that he submit "Sedona" as the name. On June 26, 1902, that name was approved.

References

1. Abbott, P.L., & Cook, D.R. (2007). *Geology Underfoot in Northern Arizona*. Mountain Press Publishing Company.
2. Blakey, R.C. (1990). Stratigraphy and Geologic History of the Pennsylvanian and Permian Rocks of the Mogollon Rim Region, Central Arizona and Vicinity. In *Geologic Excursions through the Sonoran Desert Region, Arizona and Sonora*. Arizona Geological Survey Special Paper 7.
3. Lucas, S.G., & Henderson, C.M. (2021). Conodonts and the Base of the Permian in the Mogollon Rim Region, Central Arizona. *Permophiles*, (73), 15–20.
4. Ranney, W. (2014). *Sedona Through Time: A Guide to Sedona's Geology*. Ranney & Associates Publishing.

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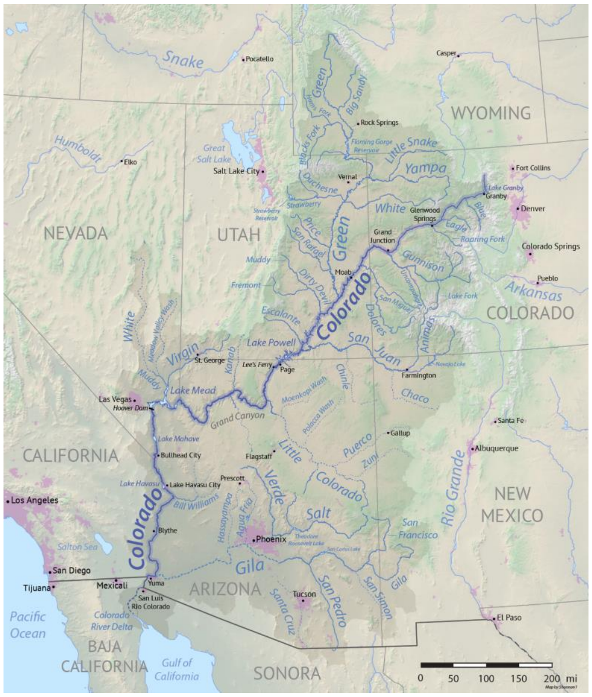
Climate Change and the Future of Arizona

Abby Keebler

Water is really important


Snake
Pocatello
Casper
WYOMING
Green
Big Sandy
Rock Springs
Humboldt
Elko
Great Salt Lake
Salt Lake City
Flaming Gorge Reservoir
Little Snake
Yampa
Vernal
Duchesne
Fort Collins
Lake Granby
Granby
Denver
NEVADA
UTAH
Strawberry
White
Glenwood Springs
Eagle
Blue
Grand Junction
Price
San Rafael
Green
Gunnison
Roaring Fork
Colorado Springs
Muddy
Fremont
Moab
Dirty Devil
Colorado
Pueblo
Arkansas
COLORADO
Escalante
Dolores
San Miguel
Lake Fork
White
Virgin
St. George
Kanab
Lake Powell
Lee's Ferry
Page
San Juan
Animas
Farmington
Las Vegas
Hoover Dam
Lake Mead
Grand Canyon
Moenkopi Wash
Chinle
Chaco
Santa Fe
Lake Mohave
Bullhead City
Little Colorado
Puerco
Gallup
Albuquerque
CALIFORNIA
Flagstaff
Zuni
Rio Grande
Prescott
Lake Havasu
Lake Havasu City
Verde
Bill Williams
NEW MEXICO
Los Angeles
Colorado
Hassayampa
Agua Fria
Salt
Phoenix
San Francisco
Blythe
Salton Sea
San Diego
Gila
Tijuana
Mexicali
Yuma
San Luis Rio Colorado
ARIZONA
Tucson
Santa Cruz
San Pedro
San Simon
El Paso
Pacific Ocean
Colorado River Delta
BAJA CALIFORNIA
Gulf of California
SONORA
0 50 100 150 200 mi

Arizona gets 36% of its water from the Colorado River, 18% from other Arizona rivers, 41% of its water from groundwater, and 5% is reclaimed. The Colorado River in particular is a critical water resource for Arizona and its neighbors yet is incredibly vulnerable to climate change.

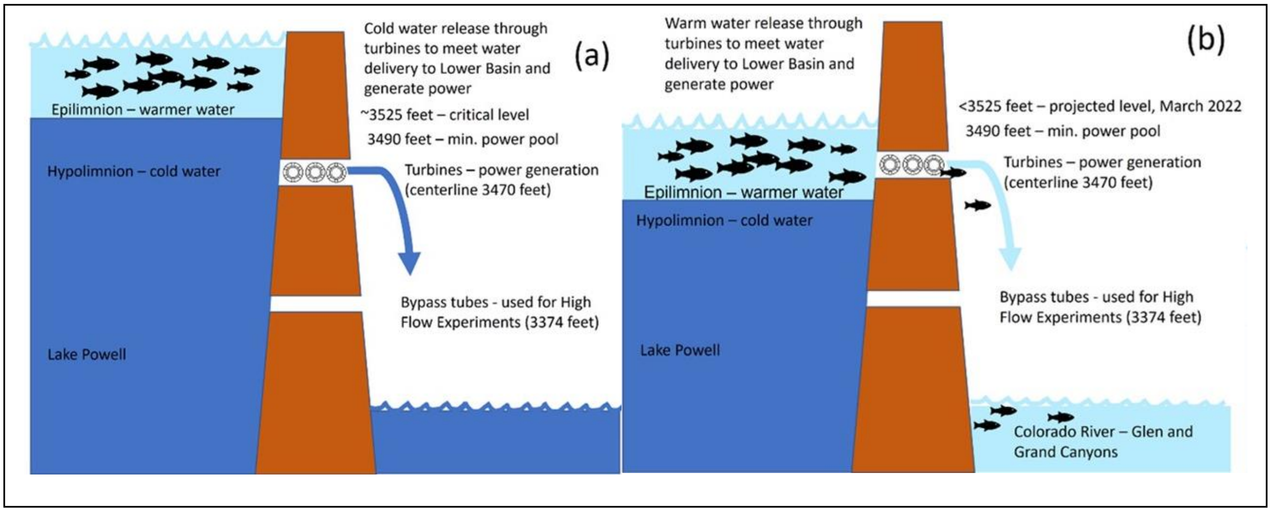
A brief explanation of Colorado River water rights:
In 1922, the seven US states encompassing the Colorado River watershed signed an agreement called the Colorado River Compact to settle usage disputes. The compact divided the Colorado River basin into the Upper Basin (Wyoming, Colorado, Utah, New Mexico) and the Lower Basin (Arizona, Nevada, California) and allocated each basin 7.5 million acre feet of the river's estimated discharge of 15 million acre feet. In 1944, the United States and Mexico signed a treaty to allocate 1.5 million acre feet of Colorado River water to Mexico. While more equitable in spirit, this now meant 16.5 million acre feet of water were allocated to various parties. The actual discharge of the Colorado River was likely less than 15 million acre feet even in 1922, and the 20-year running average is currently less than 13 million acre feet today. Furthermore, the compact did not formally allocate water to indigenous tribes, who were not present at the negotiations, which led to decades of difficulty for tribes to get the water infrastructure they needed. In 1992, Upper and Lower Basin indigenous tribes formed the Ten Tribes Partnership to advocate for better management of the Colorado River. A joint study they conducted with the Bureau of Reclamation found that Colorado River basin tribes are entitled to 2.8 million acre feet of Colorado River water, equivalent to the allocation to the entire state of Arizona.

What does Arizona use its water for?
Arizona allocates 72% of its water for agricultural use, 22% for municipal use, and 6% for industrial use. More than half of the water used for agriculture comes from river supply. In Arizona, water rights are tied to land ownership, so farmers who own their land are able to irrigate all of their fields. Recently, these policies have created new opportunities for companies to exploit the Colorado River's resources: a private company purchased farmland and then sold the water rights to a suburb near Phoenix. While the sale is being challenged in court for environmental regulations violations, growing suburban populations continue to increase municipal demands for water. Without new regulations, water investment businesses can profit at the expense of rural farming communities and Colorado River ecosystems.

How will climate change impact the Colorado River?
As the climate in the US southwest gets warmer and drier, the Colorado River experiences reduced flow due to increased evaporation, reduced precipitation, and reduced snowpack in the Rocky Mountains. Snowpack is the main water source for the Colorado River; it melts in late spring/early summer and is immediately vulnerable to

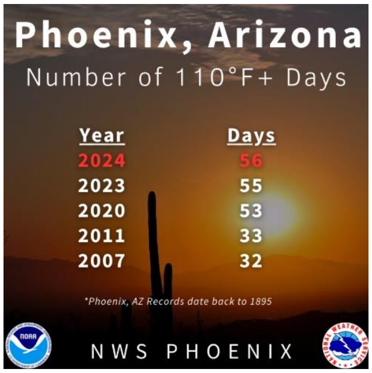
evaporation due to hot, dry temperatures. In contrast, Arizona's other rivers (Salt and Verde) may be less vulnerable to intense evaporation because they are fed by precipitation during the cooler winter months, providing more flow to fill the reservoirs. However, drought is expected to have a strong impact on all Arizona water sources.

The Colorado River gives life not just to humans living in the desert, but also many different ecosystems which are threatened by climate change. Native fish populations in the Grand Canyon are directly threatened by overuse of Colorado River water. Though the Colorado River is typically a very cold river, upper levels of water in reservoirs like Lake Powell are very warm. The warm water is an excellent environment for smallmouth bass, an invasive game fish. When the dam was built, the water level was high, so water passing through the dam was cold and came from deep in the lake. The Colorado River having less discharge means reservoirs have lower levels, so the water passing through the turbines now comes from the warmer surface layer and contains smallmouth bass (see figure). The native coldwater fish are not well adapted to warmer water temperatures and are hunted by the smallmouth bass, sometimes resulting in the loss of entire populations.


(a)
Cold water release through turbines to meet water delivery to Lower Basin and generate power
Epilimnion – warmer water
~3525 feet – critical level
3490 feet – min. power pool
Hypolimnion – cold water
Turbines – power generation (centerline 3470 feet)
Bypass tubes - used for High Flow Experiments (3374 feet)
Lake Powell
(b)
Warm water release through turbines to meet water delivery to Lower Basin and generate power
<3525 feet – projected level, March 2022
3490 feet – min. power pool
Turbines – power generation (centerline 3470 feet)
Epilimnion – warmer water
Hypolimnion – cold water
Bypass tubes - used for High Flow Experiments (3374 feet)
Lake Powell
Colorado River – Glen and Grand Canyons

The states of the Lower Basin recognize the need for water conservation and have pledged to reduce consumption. Agricultural water usage can be reduced by prioritizing crops which use less water, introducing new policies, and improving water infrastructure. Arizona used to have a 'use it or lose it' policy for agricultural water rights where farmers who did not use their full allocation would lose their water rights. This policy disincentivized water conservation, so a bill was passed in 2021 which allows farmers to work with the Arizona Department of Water Resources to conserve water for the next decade without forfeiting their water rights. As the Colorado River dries, some farmers are also being forced to switch to groundwater. Groundwater is currently mostly unregulated in Arizona, so additional legislation will be needed to address overpumping.

Other effects of climate change:



Phoenix, Arizona

Number of 110°F+ Days

Year	Days
2024	56
2023	55
2020	53
2011	33
2007	32

*Phoenix, AZ Records date back to 1895

NWS PHOENIX

ARIZONA'S CODY FIRE SCORCHES 1,000 ACRES NEAR TUCSON, PROMPTING EVACUATIONS
FOX WEATHER

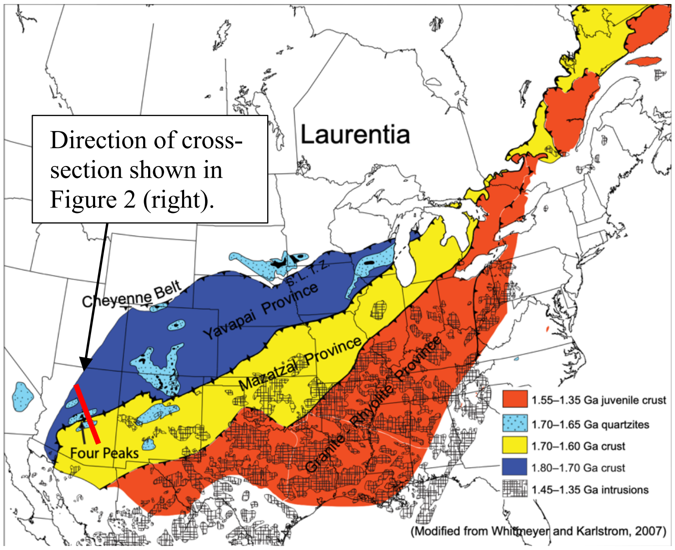
Sources: Ge (2023) Fixing the Flawed Colorado River Compact. EOS | Trammel (2024) Smallmouth Bass: Not a Small Threat to the Grand Canyon. NPS | tentribespartnership.org | Mumme (2020) The 1944 Water Treaty and the Incorporation of Environmental Values in US-Mexico Transboundary Water Governance. Environmental Science & Policy | Arizona Department of Water Resources | Scanlon (2025) Multidecacal drought impacts on the Lower Colorado Basin with implications for future management. Nature Communications Earth & Environment

Proterozoic (2.5 - 0.5 Ga)

Overview of Arizona Geologic History – Proterozoic to now. Victor Gomez

Arizona's geologic history begins with Proterozoic orogenic belts (1.8–1.0 Ga), which define a 1000-km-wide swathe of the lower United States. This juvenile crust was formed by the collisions of volcanic island arcs with the continent Laurentia.

The Mazatzal orogeny (mountain-forming event) is a central component of all tectonic models involving the Proterozoic rocks of the south-western United States. A classic exposure of Mazatzal stratigraphy is the Four Peaks region in central Arizona, which is located at the boundary of the Yavapai and Mazatzal crustal provinces. Here, the metasedimentary section was folded into a north-verging syncline (downwards fold).


Direction of cross-section shown in Figure 2 (right).
Laurentia
Cheyenne Belt
S. L. T. Z.
Yavapai Province
Mazatzal Province
Granite - Rhyolite Province
Four Peaks
1.55–1.35 Ga juvenile crust
1.70–1.65 Ga quartzites
1.70–1.60 Ga crust
1.80–1.70 Ga crust
1.45–1.35 Ga intrusions

(Modified from Whitmeyer and Karlstrom, 2007)

Figure 1: Proterozoic provinces of North America. The cross-section in Figure 2 (right) is shown in red (Mako & Williams, 2015)

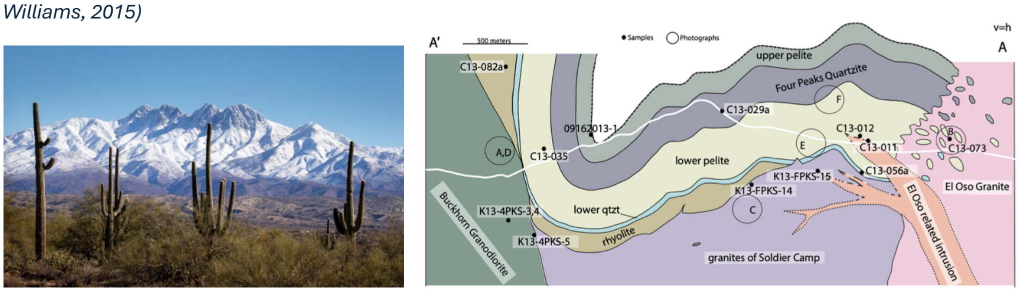

A′
500 meters
Samples
Photographs
v=h
A
C13-082a
upper pelite
Four Peaks Quartzite
F
C13-029a
09162013-1
A,D
C13-035
lower pelite
E
C13-012
C13-011
B
C13-073
C13-056a
K13-FPKS-15
K13-FPKS-14
El Oso Granite
Buckhorn Granodiorite
K13-4PKS-3,4
lower qtzt
C
K13-4PKS-5
rhyolite
El Oso related intrusion
granites of Soldier Camp

Figure 2: Left: Four Peaks Wilderness Area Photograph. Right: Cross-section showing the stratigraphy. The syncline formed in the Mazatzal orogeny is visible (Mako & Williams, 2015)

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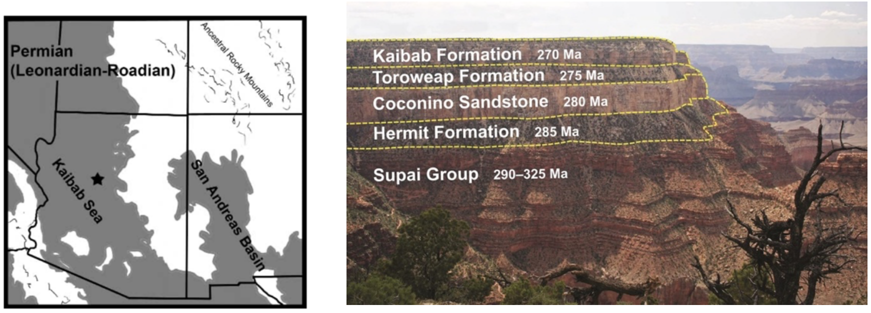
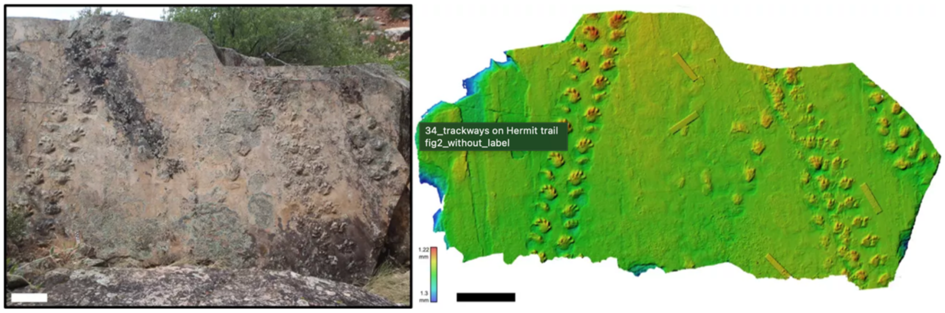

Permian
(Leonardian-Roadian)
Ancestral Rocky Mountains
Kaibab Sea
San Andreas Basin
Kaibab Formation 270 Ma
Toroweap Formation 275 Ma
Coconino Sandstone 280 Ma
Hermit Formation 285 Ma
Supai Group 290–325 Ma

Figure 1: Left: location of the Kaibab Sea responsible for deposition of the Kaibab Formation sandstone (Hodnett & Elliott, 2013). Right: strata of the Grand Canyon (National Parks Service, 2025)

The Paleozoic sandstone is rich in plant fossils, marine fossils, and track fossils of early reptiles. The Coconino sandstone, shown in the Grand Canyon cross-section (Figure 3), is home to Diadectomorph tracks from the ancient desert environment.



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The first half of the Mesozoic marked the end of the tectonic calm of the region. The supercontinent Pangea rifted, creating the Atlantic Ocean and causing volcanism in the Western United States that continues to this day. An example of this early volcanism is the eruption that created the Montezuma Caldera (10-11 miles in diameter), which contains the Coronado National Memorial in southern Arizona. Uplift caused the Paleozoic oceans to disappear, and Arizona became populated by large dinosaurs. Arizona is home to dinosaur track fossils, and many large skeletons have been discovered over the years. Towards the end of the Mesozoic, there was another period of geologic calm. This, combined with the encroachment of the Gulf of America (please don't deport me), caused the deposition of the Bisbee Group. Another large sedimentary formation that covers the state.

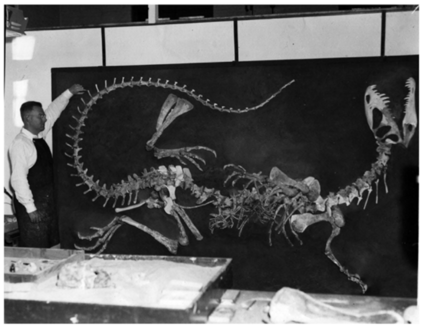

Figure 3: Dr. Wann Langston posing with the skeleton of Dilophosaurus wetherilli in the early 1950s. (Marsh & Rowe, 2020)

Cenozoic (60 Ma – Present)

In the beginning of the Cenozoic, the tectonic calm came to an end. The subduction of the ancient Farallon plate underneath North America caused uplift and volcanism. Over time, (around 30 Ma) the fault became the modern strike-slip fault we know today and created the set of ranges and valleys (horst and graben features) of the Basin and Range Provinces that dominate the geology of the region today.

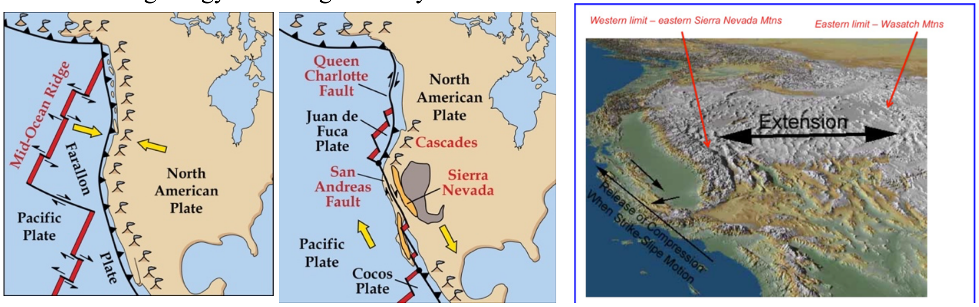

Figure 4: Left: Tectonic boundaries 40 Ma. Center: Tectonic boundaries today (National Parks Service, 2025). Right: formation of horst and graben features of the Southwestern United States. (University of Wisconsin-Madison, 2025)

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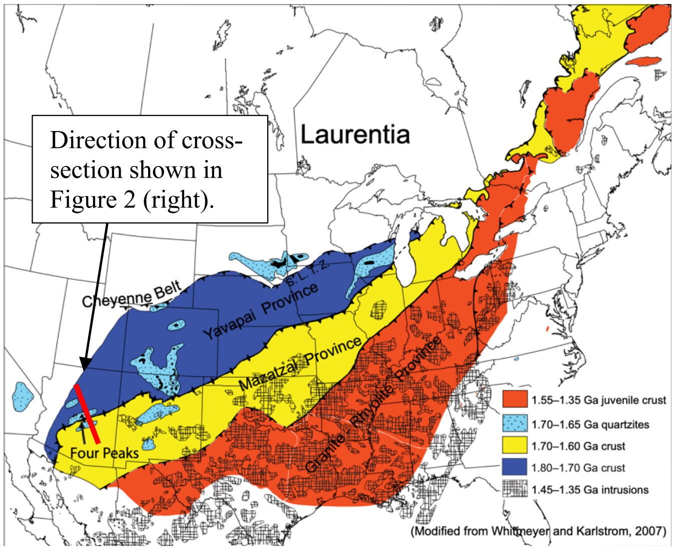
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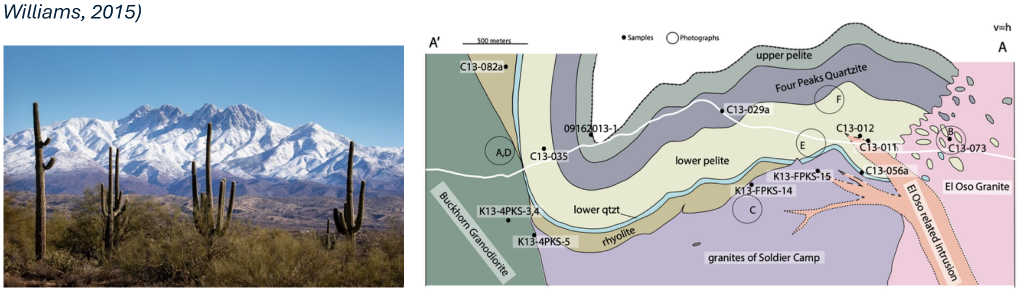
A′
500 meters
Samples
Photographs
v=h
A
C13-082a
upper pelite
Four Peaks Quartzite
F
C13-029a
09162013-1
A,D
C13-035
lower pelite
E
C13-012
C13-011
B
C13-073
C13-056a
K13-FPKS-15
K13-FPKS-14
El Oso Granite
C
Buckhorn Granodiorite
K13-4PKS-3,4
lower qtzt
K13-4PKS-5
rhyolite
granites of Soldier Camp
El Oso related intrusion

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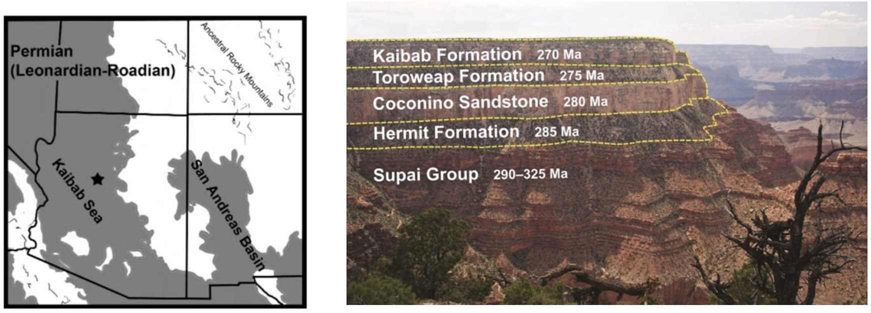
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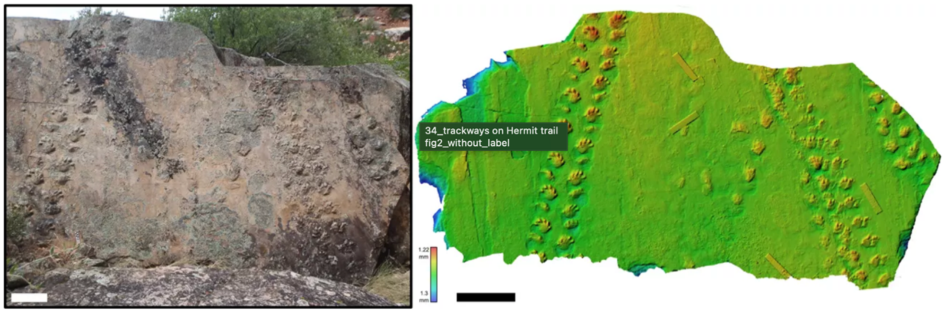
34_trackways on Hermit trail
fig2_without_label
1.22 mm
1.3 mm

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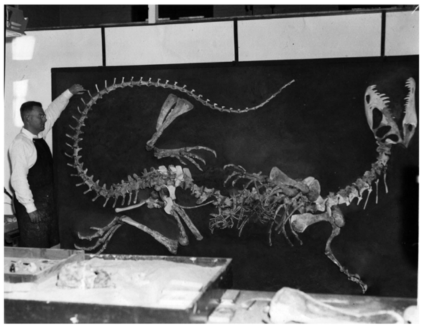

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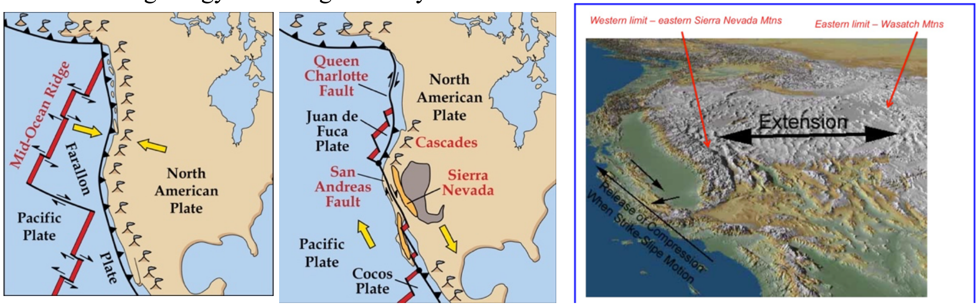
Mid-Ocean Ridge
Farallon
Plate
Pacific Plate
North American Plate
Queen Charlotte Fault
Juan de Fuca Plate
North American Plate
Cascades
San Andreas Fault
Sierra Nevada
Pacific Plate
Cocos Plate
Western limit – eastern Sierra Nevada Mtns
Eastern limit – Wasatch Mtns
Extension
Release of Compression When Strike-Slipe Motion

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The Petrified Forest of the Chinle Deposit

Maia Hannahs

The Chinle Deposit, which contains the petrified forest is a large sedimentation of deposits from early mezazoic rivers, lakes and swamps. The state of the deposits have been dates to range from 215-221 million years ago and contain many fossils of flora and fauna collecting int he deposition of these ancient lake beds, water erosion of deep chanels into this deposit have allowed the state to be accessed easily. The Chinle deposit has been a long topic of study for its accessible fossil record and its easily identifiable strata, which also demonstrates the process of fossilization. One of the most notable features of the national park is the petrified forest. Extensive fossilization of an ancient forest in this deposit has provided many samples that not only review the biology of the early mesozoic but also provide invaluable evidence of the process and extent of petrification[2].

The lowest and thus oldest region of the Chinle deposit is a mudstone deposit known as the Blue Mesa Member, which dates back to 225 million years ago (MYA), followed by a mudstone and sandstone conglomerate known as the Sonsela member which ranges from 220 MYA to 108MYA.[2] The petrified forest is largely mudstone and contained in the upper part of the Sonsela member. To the north of the park there is an upper layer known as the owl rock formation which is more recent than these strata. This petrified forest section was deposited from about 225-207 MYA which spans at least 17.4 MYA according the Uranium dating of Zircon collected from the strata of the deposit, this would place this deposit in the late triassic (much of the Norian division of the triassic period). Much of the source of these deposited debris was rhyolitic tephra (glassy volcanic debris) from the include the High Rock Caldera Complex and the McDermitt Calderas.[4]

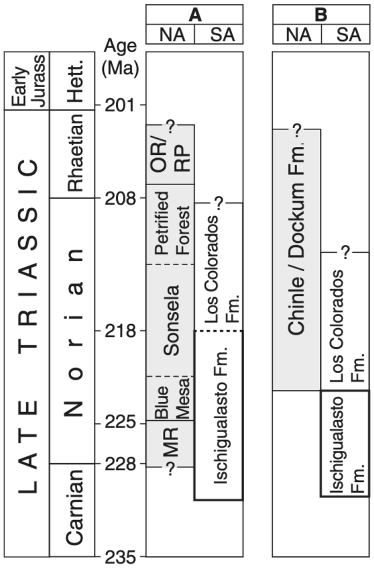


Figure 1: Chronological and spacial arrangement of strata in the Chinle formation

The environment which formed the species preserved in the Sonsela member which was a warm climate with highlands, low lands and swamps, thus contained a wide variety of flora. The lowlands consisted of a wide flood plain which contained aquatic plants and animals, adjacent to this was a coniferous forest which provided much of the wood which became the petrified forest. This ancient forest contained an understory of ferns and cycad like seeding plants (bennettitites) and a Coniferous canopy of Araucarioxylon arizonicum and other gymnosperms. The Araucarioxylon arizonicum conifers make up the majority of the petrified forest material, some of which is from logjams of fallen material and some of which is still in a upright position, indicating periods of sudden flooding which would have sedimented the living trees in place and allowed the process of silicification to begin and eventually creating the petrified forest.[2, 5]

Silica is the must abundant mineral in the crust, is highly biocompatible and hydrophilic, and thus is one of the most common minerals which fossilize living remains (the other common one being goethite). Many plants contain small amounts of silica even in life but in the petrification process soluble and colloidal silica is taken up through the plants vascular system and slowly deposited within.[1] At ambient pressures and temperatures Silica is not highly soluble in water but a small amount can become silicic acid in solution, this is a silica species terminated with hydroxyl groups. This is highly soluble species and readily condenses not only onto other silica through a bridging oxygen but can bind to other hydroxyl groups in carbonaceous materials in the decaying wood. The condensation of silica can happen very quickly, provided a sources of soluble silica, most can condense out of solution in a mater of hours, this property is used for chemical engineering of of silica microspheres and sol gels which are incredibly important to modern medical technology. In natural sources of highly silicified water (such as a hot spring) wood can take on measurable amounts of silica within years.

In the fossilizing environment of the petrified forests, a few different processes take place. Silica must have and environmental source, it much be taken up and transported internally in the wood, and the original material of the plant must be removed by chemical or biological processes in tandem with the addition of silica, and of course some diffusive medium to transport these species, which would be water. The exact ordering and details of these processes is not well understood and higher context dependent and thus has only been investigated for the case of the petrified forest. The solubility of silica species can be easily investigated in the laboratory and is well understood from the chemistry aspect but the rate of transport and removal of the organic material has a number of proposed mechanisms and is expected to need a combination of processes, as well as the added mystery of the exact materials that would be present at various stages.

Solubilized or colloidal silica can be taken and transported via the vascular system of plants, even full silica particles. This has been demonstrated to be possible on very short time scales in laboratories, and organic templating of silica is a manufacturing method in which an organic matrix (often wood) is infused with silica species to create porous SiC structures from bonding silica with the carbon matrix of the plant.[1, 4] The properties of the material which the silica species are replaces does have an effect on the fossilization process, but not specific enough to the species of tree which is being silicified. One of the most noticeable properties which has been observed in Cenozoic samples (so more recently silicified wood than the Mesozoic samples of the petrified forest) is the way the hydrophobic intercellular region is the last area to silicify. This hydrophilic intracellular area which allows for the transport of water soluble nutrients, silicifies first as it can most easily take up the soluble silica species. The samples in figure 2 show the build up of this silica phase on the inside of each cell. Thus first a negative builds where the material fills in the cells matrix, then the lignin, which makes up the structures around the cells gets replaces later.

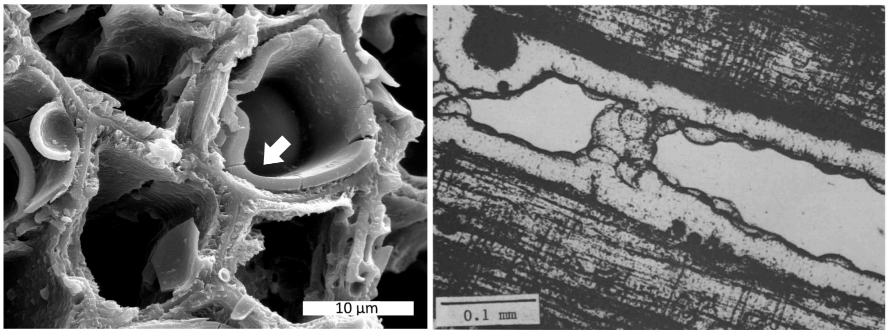


Figure 2: build up silica on the inside walls of plant cells in Cenozoic petrified wood.[4] (b) thin section of a partly silicified [3]

The serial removal of plant material is where much of the confusion about the exact pathways of silicification. The structure and properties of the specific material being removed from wood could have a myriad of effects. Wood contains tannins, which are water soluble compounds that tend to be acidic, lignin and cellulose, are distinctly hydrophobic and hydrophilic respectively. Thus there is a complex array of microenvironments encountered by soluble silica as it is taken up by the silica. In lab settings, the condensation of silica Is controlled at the macro scale where the pH and temperature of the environment controls the materials, this generally allows silica ton condense into uniform amorphous networks or spherical particles. Some of the behavior of sol-gel and colloidal silica can be seen in the silicification of of wood.

Colloidal silica has a tendency to form botryoidal masses as after the initial nucleation from solution, the growth continues through very small monomers or oligomers of silica, which due to the non directionality of the surface energy of an amorphous material, grows in round shapes. As stated before silica is not very soluble in water, In labs silicic acid is usually used in the form of tetra-ethyl-ortho-silicate (TEOS) which hydrolyzes into silicic acid in solution as the ethyl groups dissociate. Some silicic acid can form just from water, ionic species can charge balance broken bonds in silica networks, except for at very low pH (less than 3) the silica spices is anionic in solution, therefore the inclusion of alkali ions can stabilize this species in solution. In laboratory settings, the inclusion of salts can suppress nucleation of silica nano particles which keeps the silica in solution.

The amorphous structure of silica is what allows it to so closely replicate the morphologies of the cells. Due to its lack of crystal structure, amorphous material have little thermodynamic advantage of adopting specific morphologies, like the way crystals grow in facets. Many fossilized species contains multiple forms of silica, however one species tends to dominate in a particular specimen. This suggests that the initial silicification generally is in an amorphous structure, and it is a secondary geologic process which can cause the crystallization of this material.Opal contains molecular water which it easily fits into its amorphous structure, chalcedony is denser but still amorphous which generally is possible due to terminating hydroxyl groups in the Si-O network. Quartz and Feldspar are crystalline and do not contain this free volume save for defects and crystal grains. This densification through crystallization tends to destroy the original structure of the cells as crystalline facets grow and water is removed.

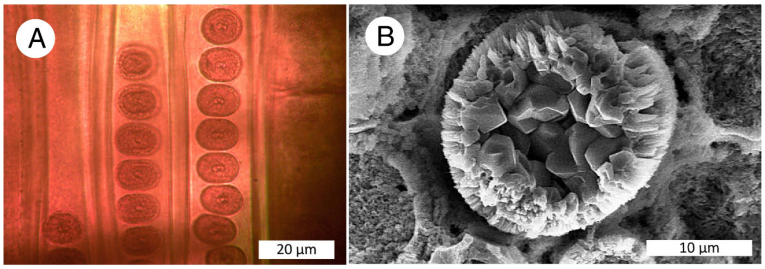
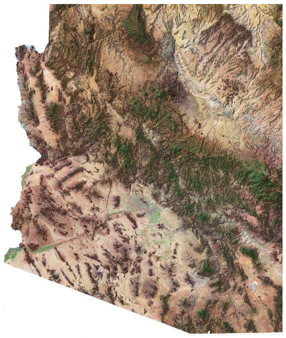


Figure 3: microscopic images of Silicified samples from Nevada's petrified forest

The early stages of petrification can be replicated in labs, solvation of Silica species, its nucleation and interaction with decaying organic material, and the degradation of organic materials through chemical means is all easily replicated. Much study of these process is already taken on an a possibility for engineering of porous silica. However the subsequent geologic processes, the interaction between the removal of organic material in relation for the replacement with silica is still seen as very context specific and not fully understood.[4]

Sources

1. Mustoe, George E. 2023. "Silicification of Wood: An Overview" Minerals 13, no. 2: 206. https://doi.org/10.3390/min13020206
2. Ramezani, J., G. D. Hoke, D. E. Fastovsky, S. A. Bowring, F. Therrien, S. I. Dworkin, S. C. Atchley, and L. C. Nordt. 2011. "High-Precision U-Pb Zircon Geochronology of the Late Triassic Chinle Formation, Petrified Forest National Park (Arizona, USA): Temporal Constraints on the Early Evolution of Dinosaurs." *Geological Society of America Bulletin* 123 (11-12): 2142–59. https://doi.org/10.1130/b30433.1.
3. Scurfield, G., and E.R. Segnit. 1984. "Petrifaction of Wood by Silica Minerals." *Sedimentary Geology* 39 (3-4): 149–67. https://doi.org/10.1016/0037-0738(84)90048-4.
4. Mustoe, George E. 2015. "Late Tertiary Petrified Wood from Nevada, USA: Evidence of Multiple Silicification Pathways" Geosciences 5, no. 4: 286-309. https://doi.org/10.3390/geosciences5040286\
5. Sigleo, Anne C. 1979. "Geochemistry of Silicified Wood and Associated Sediments, Petrified Forest National Park, Arizona." Chemical Geology 26 (1-2): 151–63. https://doi.org/10.1016/0009-2541(79)90036-6.



Seeing Arizona's Green Pulse from Space

What Chlorophyll Fluorescence Reveals about Primary Production

Zichang He | Ge 136 | Spring 2025

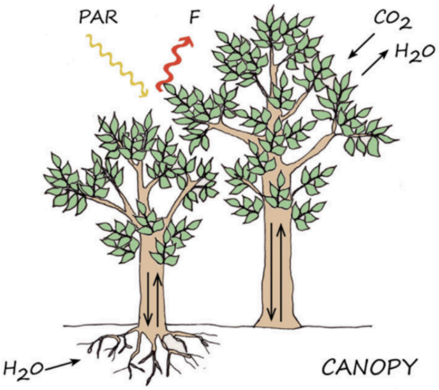


Figure 1. Canopy photosynthesis and fluorescence [1]

Fluorescence: A Clue for Photosynthesis

Solar induced chlorophyll fluorescence (SIF) emerged as a byproduct of leaves absorbing light for photosynthesis. By absorbing photons, electrons in chlorophyll molecules are raised from ground state to higher energy levels. After that, most of the energy is transferred by the photosystem to adjacent pigments or photoreaction centers, some are dissipated via heat, and only a small portion is reemitted as fluorescence photons. Chlorophyll fluorescence appears to have a double-gaussian shape, with peaks in red (~ 680 nm) and far-red (~740 nm) regions, which are in general set by the energy gap between the first excited state and the ground state.

Contrary to what one might assume, fluorescence intensity actually scales with plants' photosynthetic activity, within the detectability of a satellite. Though an individual photon ends up either fueling the breakdown of H_2O or being wasted, the more total light absorbed, the more energy is available for *both* photosynthesis and the associated fluorescence emission. Moreover, chlorophyll fluorescence and photosynthesis could vary concomitantly in response to water and temperature stress, under which non-photochemical quenching plays an important role in downregulating the effective photons for *both* two processes. This lays the foundation for approximating gross primary productivity (GPP) using measurement of fluorescence [1].

Satellite Retrieval of the Weak Luminescence

Chlorophyll fluorescence that transmits the atmosphere is remarkably weak, roughly 1 W/m2/µm/sr, while the radiance reflected by the canopy is typically 100 W/m2/µm/sr - a hundred times brighter. However, there are some windows in the spectrum, featuring solar or atmospheric absorptions, that provide dark background and make fluorescence retrieval possible. This is achieved by detecting the change of fractional depth in these spectral windows [2]. Specifically, when a stream of sunlight penetrates through the atmosphere and bounces off the earth's surface, the absorption features are retained just like its fingerprints. Imagining chlorophyll like a tiny bulb emitting faint glow at specific wavelengths and filling in the dips in the reflectance spectrum, the fingerprints are no longer preserved. By measuring the filling-in - how shallower the dips become - one can determine the intensity of the chlorophyll fluorescence coming from the plants.

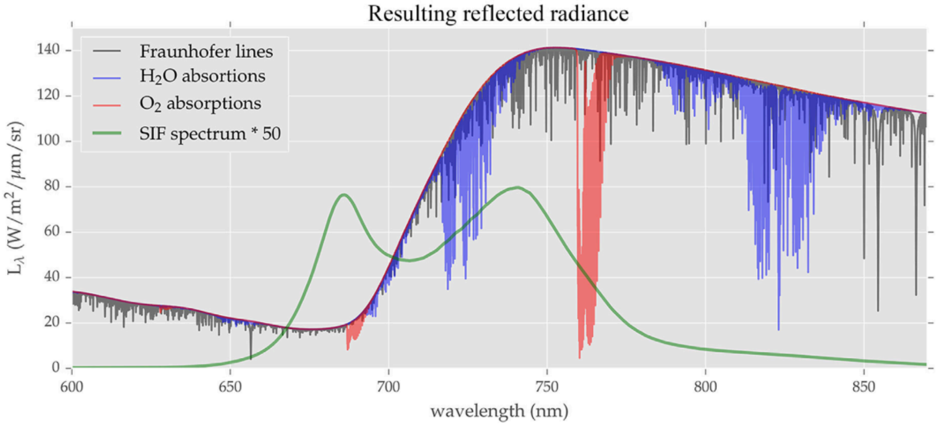


Figure 2. Absorption features in reflectance spectrum and solar induced fluorescence spectrum [2].

$$\mathrm{GPP} = \mathrm{SIF} \times \frac{\mathrm{LUE}}{\Phi_F \times \Omega_C}$$

Advancement of Greenness in Arizona

Estimating primary productivity from chlorophyll fluorescence requires one more piece quantifying the GPP-SIF relation, which usually involves parameterizing fluorescence yield (Φ_F), light use efficiency of converting light to photochemical energy and downstream carbon assimilation (LUE), and a factor accounting for canopy reabsorption (Ω_C). These parameters are closely related with biome composition, canopy structure, and plants' physiological change in response to abiotic environmental conditions.

By synthesizing fluorescence measurements from Fourier Transform Spectrometer onboard the Orbiting Carbon Observatory-2 (OCO-2) [3], and parameterizations from CliMA-Land model [4], we are able to gain insights into Arizona's plant photosynthetic activity. Roughly estimated, biomass in Arizona takes up ~ 50 TgC/yr (1 Tg = 10^{12} g) annually, which is equivalent to the weight of a million bowhead whales. A large portion of atmospheric CO_2 uptake is attributable to forests and grasslands in central and southeast Arizona, with an apparent seasonal cycle predominantly controlled by temperature variation. Intriguingly, GPP reaches a plateau before June and further peaks around the late summer. The steppiness is potentially associated with a greening in southeast Arizona in July and August, when summer monsoon brings abundant precipitation. Continuous radiative heating on this dryland during summer leads to convergence of air mass and the southerly winds transport low-level moisture, triggering heavy precipitation episodes [5]. Additionally, sporadic green hotspots near the river and city of phoenix are related to agricultural practice.

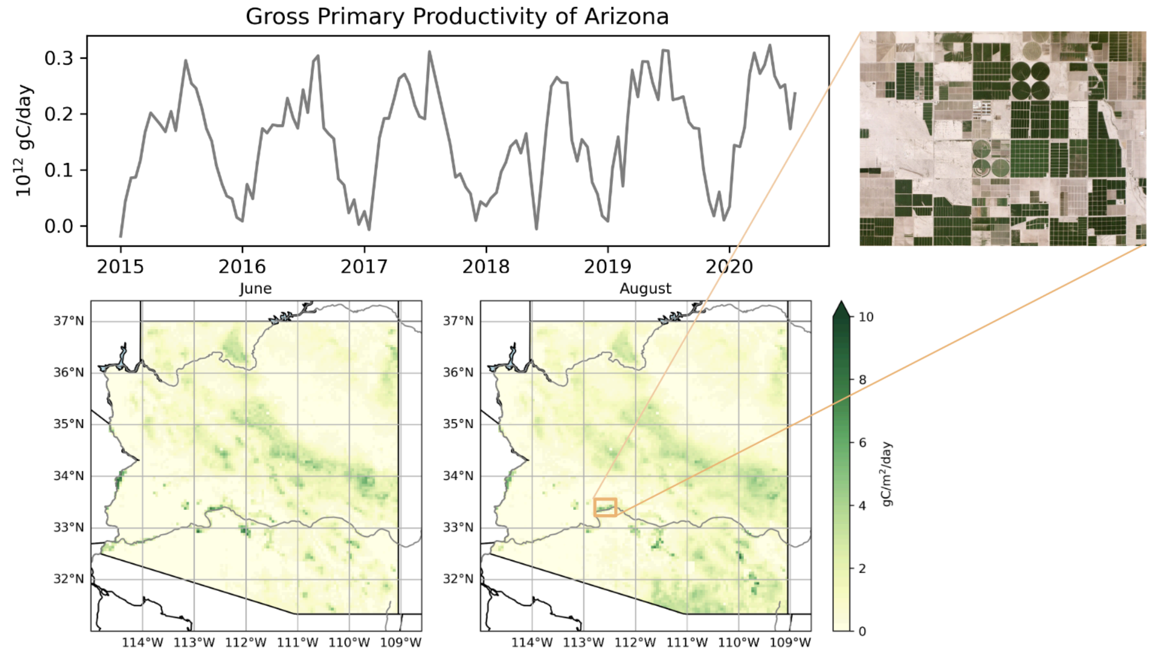


Figure 3. Estimation of gross primary productivity across Arizona. Satellite image of irrigation system © Wikimedia Commons

Reference

[1] Porcar-Castell, Albert, et al. "Linking chlorophyll a fluorescence to photosynthesis for remote sensing applications: mechanisms and challenges." Journal of experimental botany 65.15 (2014): 4065-4095.

[2] Frankenberg, C., and J. Berry. "Solar induced chlorophyll fluorescence: origins, relation to photosynthesis and retrieval. Comprehensive Remote Sensing 3: 143-162." 2018.

[3] Yu, L., J. Wen, C.Y. Chang, C. Frankenberg, and Y. Sun. 2021. High Resolution Global Contiguous SIF Estimates from OCO-2 SIF and MODIS, Version 2. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1863

[4] Doughty, Russell, et al. "A novel data-driven global model of photosynthesis using solar-induced chlorophyll fluorescence." Authorea Preprints (2023).

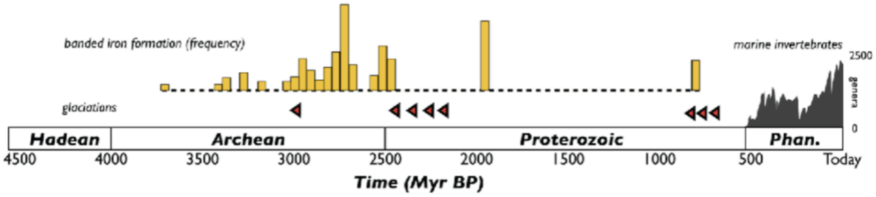
[5] Basics of the Arizona Monsoon & Desert Meteorology | School of Geographical Sciences and Urban Planning. (n.d.). https://sgsup.asu.edu/basics-arizona-monsoon-desert-meteorology

Banded Iron Formations and the Pikes Peak Iron Formation

Emma Isella – Ge136c 2025

Background

Hamersley formation in Australia (USGS).

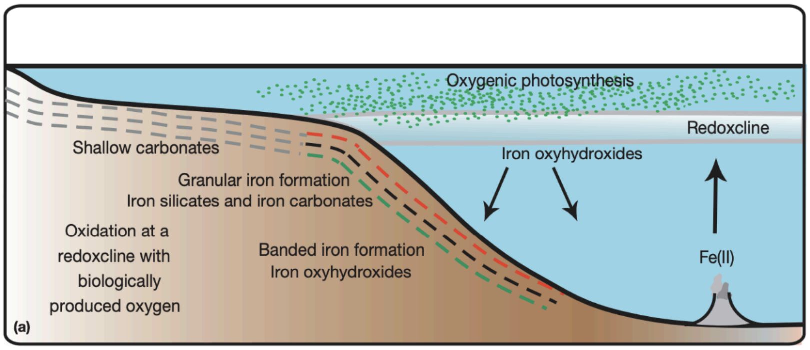


BIF frequency over time (Ge11b lecture notes).

Banded iron formations (BIFs) are distinctive units of sedimentary rock consisting of alternating layers of iron oxides and iron-poor chert. These are almost exclusively Precambrian formations, with the majority of BIFs dating to the late Archaean (2,800-2,500 Ma), predating the Great Oxidation Event (GOE). These formations are found worldwide on every continental shield. They are also important for economic geology, as they account for around 60% of global iron reserves. Most iron deposits that are being mined are BIFs.

How are BIFs formed?

The formation of BIFs relies on the redox chemistry of iron in its ferrous (Fe^{2+}) and ferric (Fe^{3+}) forms. Ferrous iron is soluble in water, while ferric iron precipitates and appears as reddish-brown. Ferrous iron enters the surface Earth system via continental weathering and emissions from hydrothermal vents. BIF formation required a high concentration of ferrous iron in the oceans, which means that the atmosphere and water had to be broadly anoxic. Even a low level of oxygen makes the environment very oxidizing, which would have prevented ferrous iron accumulation by oxidizing it and precipitating it out of the ocean. From this ferrous iron-rich ocean, there would have been a change that triggered the oxidation of the ferrous iron, leading to the precipitation of iron oxides that eventually became the BIFs. The exact mechanism of this oxidation is unknown, but there are three popular hypotheses.



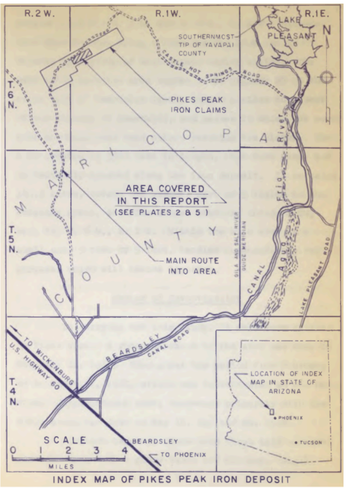
Classical explanation for Fe^{2+} oxidation (Bekker et al., 2014).

The classical explanation is direct oxidation from free oxygen produced by photosynthetic cyanobacteria (Cloud 1965, 1973). Ferrous iron-rich waters would have been upwelling from below while cyanobacteria would have been in the upper photic zones, producing oxygen. At the interface between the fronts of oxygenated water from above and ferrous iron-rich water from below, ferric iron would have been produced and precipitated in the following reaction:

$$2Fe^{2+} + 0.5O_2 + 5H_2O \Leftrightarrow 2Fe(OH)_3 + 4H^+.$$

An alternative popular idea is that of direct metabolic ferrous iron oxidation, which could occur through two primary mechanisms (Bekker et al. 2014). One involves microaerophilic ferrous iron oxidizers, which are microbes that use ferrous iron as an electron donor and oxygen as an electron acceptor to reduce CO_2 to organic carbon in the following reaction: $6Fe^{2+} + 0.5O_2 + CO_2 + 16H_2O \Leftrightarrow [CH_2O] + 6Fe(OH)_3 + 12H^+$. Organisms with this metabolism are widespread in marine systems today. Under low oxygen conditions, this process operates at 50 times the rate of abiotic iron oxidation, so it has the potential to be relevant in dominating the iron cycle during the pre-GOE era, if it existed. The other common metabolism involving ferrous iron oxidation is photoferrotrophy, which is anaerobic photosynthesis that uses ferrous iron as an electron donor: $4Fe^{2+} + CO_2 + 11H_2O \Leftrightarrow [CH_2O] + 4Fe(OH)_3 + 8H^+$. Examples of organisms with this metabolism include purple and green sulfur bacteria. This metabolism was thought to be common on the early Earth. These metabolic explanations are plausible, as modelling has been done to show that even modest populations of these organisms could account for the deposition of these iron formations. As a modern-day analogue, Lake Matano in Indonesia has metabolic ferrous iron oxidation driving the deposition of significant iron-rich sediments (Crowe et al. 2008).

A fully abiotic explanation for BIF formation is the photo-oxidation of ferrous iron by ultraviolet light (Cairns-Smith 1978). This is based on the idea that before the GOE, there was no protective ozone layer, so the early Earth experienced a high flux of UV photons, leading to the photo-oxidation of Fe(II): $2Fe^{2+}(aq) + 2H^{+} + h\nu \Leftrightarrow 2Fe^{3+}(aq) + H_2$. This reaction has been shown experimentally to proceed readily in acidic water exposed to light with wavelengths between 200-300 nm. The ferric iron was then hydrolyzed and precipitated as ferric oxyhydroxide.



Pikes Peak Iron Formation map (Sharp, 1963).

Pikes Peak Iron Formation

The Pikes Peak Iron Formation is located in north-central Maricopa County, Arizona. It is part of an area of regionally metamorphosed rocks of the older Precambrian Alder group of the Yavapai series. It is described as having steeply dipping, elongated, lenticular bodies mostly composed of black specular hematite ($Fe^{3+}{}_2O_3$) and admixed magnetite ($Fe^{2+}Fe^{3+}{}_2O_4$) alternating with fine-grained quartz of different colors (Sharp, 1963). According to a 1976 record, the U.S. Bureau of Mines tested the deposit and estimated it included 100 million tons of material of 30% iron content. It was bought by the Kaiser Steel Corporation in 1961 for $1,500,000 and was drilled beginning in 1962 (Arizona Geological Survey, 2002).

Creationists and the Pikes Peak Iron Formation

The first result from Google when querying for “Pikes Peak Iron Formation Arizona” yields this study by the Creation Research Society: “A Preliminary Report on the Precambrian Pikes Peak Iron Formation Yavapai County, Arizona” (Froede Jr et al., 1998). They concluded from examining these outcrops that “the Precambrian Yavapai Series and the Pikes Peak Iron Formation formed during the earliest stages of the Flood (Lower Flood Event Division) in a volcanic setting (possibly including hydrothermal activity) under subaqueous conditions.” This came from re-interpretation of the sedimentary deposits and other physical evidence within the context of a “biblical-catastrophic framework” rather than a uniformitarian approach (as they describe it), which focuses on the energy conditions under which sediments would have been deposited rather than the passage of time. This allows them to eliminate the idea that there are paleo-depositional environments that exist for millions of years. Precambrian strata are thus classified as follows: any layers with fossils or organic matter are designated as “flood deposits, while strata without evidence of life date to the Creation week. Since there were no fossils or organic material in the Pikes Peak BIF, they establish that it dates back from the earliest stages of Noah’s Flood, because of the high energy levels required to create the sediments, bury them under thousands of feet of other sediment, and then re-expose them at the surface via erosion again.

Interestingly, the Pikes Peak BIF appears in another debate among creationists in 2016 and 2017 in the Journal of Creation. One group attempted to unify uniformitarian Precambrian time to Bible history (Dickens, 2017), which was unacceptable to young-Earth creationists as it apparently “defin[ed] and appl[ied] specific uniformitarian geologic time intervals ad hoc to biblical history” (Froede Jr, 2017). In the absence of fossils that enable biostratigraphic dating, radiometric dating is an acceptable method to date rocks. However, they use an idea of “accelerated nuclear isotope decay” to reach numbers consistent with predictions from the Bible. The rebuttal paper concluded that the Pikes Peak BIF is “best interpreted as a product of the Flood, not the Creation Week” (Froede Jr, 2017). I thought the concluding quote from Dickens’ response was entertaining: “When God created, He brought order to the universe even in atoms and continents, for God is not the author of confusion (1 Corinthians 14:33). Thus there should be harmony between God’s Word and His Creation. Despite the complexity, we should not discount the order in observable, mappable Precambrian geology and associated measurable isotopic and chemical trends. Correlating such trends and patterns with God’s Word is not naturalism.”

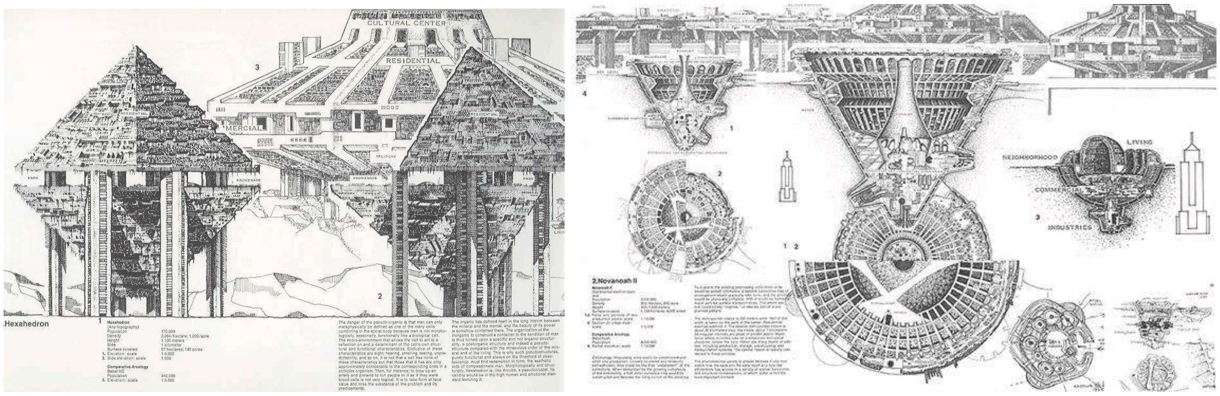
References

Arizona Geological Survey (File No. MS-4155); Bekker, A. et al. *Elsevier* (2014); Cairns-Smith, A.G. *Nature* (1978); Cloud, P.E. *Science* (1965); Cloud, P. E. *Economic Geology* (1973); Crowe, S.A. et al. *Limnology and Oceanography* (2008); Dickens, H. *Journal of Creation* (2017); Froede Jr.,C.R. et al. *Creation Research Society Quarterly* (1998); Froede Jr., *Journal of Creation* (2017); C.R. Sharp, R.R. (1963)

Kyle Hunady

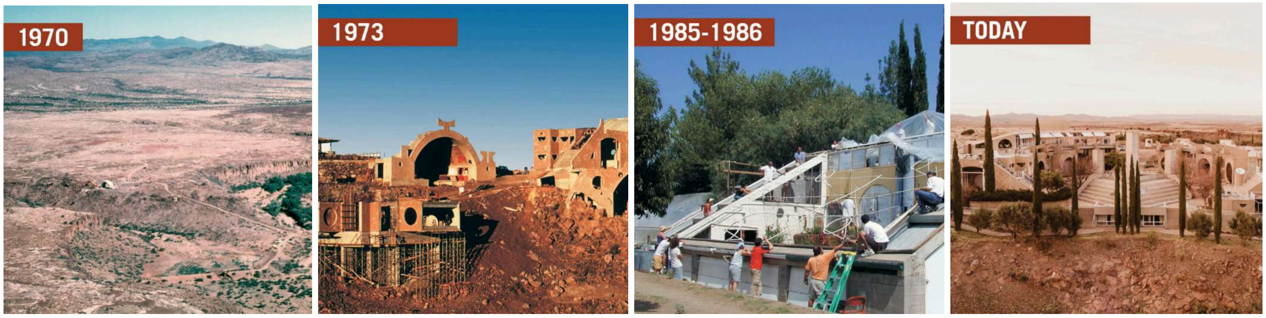
Arcosanti: An Urban Experiment in the Arizona Desert

Arcosanti was founded in 1970 by architect Paolo Soleri as a response to urban sprawl, environmental degradation, and consumer culture [1]. A former apprentice of Frank Lloyd Wright, Soleri coined the term “arcology”—a fusion of architecture and ecology—to describe compact, sustainable cities designed to minimize environmental impact and foster close-knit communities. His nonprofit, the Cosanti Foundation—from the Italian “cosa” (thing) and “anti” (against)—embodied his critique of materialism and unchecked growth. Arcosanti was conceived as a working prototype: a city for 5,000 people built in harmony with the land and its resources.



A couple concept drawings from Soleri’s *Arcology: The City in the Image of Man.* [2]

Soleri published his vision in *Arcology: The City in the Image of Man* (1969), and the following year broke ground on an 860-acre site in the Arizona desert. Located 70 miles north of Phoenix, Arcosanti has been designed around its environment. The structures sit directly on basalt bedrock, eliminating the need for large concrete foundations. Vaults, apses, and terraces are cast using natural silt molds, minimizing waste while visually blending with the desert landscape. Buildings are oriented to capture winter sunlight and provide summer shade, and a greywater system recycles water to irrigate gardens grown without synthetic pesticides or fertilizers. The city is intentionally pedestrian-scaled, designed for low environmental impact and high spatial efficiency.



Over the past 50 years, Arcosanti has been built by thousands of volunteers and on-site artisans using natural materials and environment-focused design. Although it was originally designed to house 5,000 people, the community today is home to approximately 50 residents [1].

Construction was carried out by waves of students and volunteers who joined multi-week workshops to learn building techniques and live in the community. Over the decades, more than 8,000 people contributed to Arcosanti's development. While progress was slow and often nonlinear, Arcosanti evolved into a living laboratory for Soleri's principles, emphasizing education, minimalism, and direct engagement with the land.

Community Livelihood

Despite its small population, Arcosanti sustains itself through a blend of craft, education, and culture. Its signature bronze and ceramic wind bells, made using silt-casting techniques, are sold worldwide. The community also hosts workshops, internships, and occasional events like the FORM music festival, drawing people interested in sustainable living, design, and art. Additional support comes from visitors and donations. These activities help fund operations and preserve Arcosanti as both a physical space and an educational platform.

Arcosanti artisans craft ceramic bells using natural silt casting molds. Their sales help fund ongoing projects and support the community's livelihood [1].

Looking Forward

More than 50 years after its founding, Arcosanti faces a pivotal question about its future. Its population remains a fraction of the original vision, development has slowed, and its aging infrastructure reflects its handcrafted origins. Modern sustainability technologies—like solar panels and composting systems—remain largely untapped. When Paolo Soleri stepped down in 2011, the community was left to evolve without his direct guidance [3].

Now under new leadership, and with limited capital, Arcosanti is weighing whether to modernize its facilities, expand housing, and re-engage with the broader world. Should it grow and welcome new residents, even if that means adapting its ideals? Should it become a preserved architectural landmark? Or should it remain a small artisan community, focused on simplicity and connection to nature? Whatever direction it takes, Arcosanti continues to model a different way of building and living—rooted in ecological awareness, collaboration, and the belief that cities can exist in harmony with their environment.

[1] Cosanti Foundation. Arcology. https://www.arcosanti.org/arcology/

[2] ArchDaily. Paolo Soleri's Arcosanti: The City in the Image of Man. https://www.archdaily.com/159763/paolo-soleris-arcosanti-the-city-in-the-image-of-man/arcobp

[3] Pogrebin, Robin. An Early Eco-City Faces the Future. The New York Times, 16 Feb. 2012. https://www.nytimes.com/2012/02/16/garden/an-early-eco-city-faces-the-future.html

The Navajo Nation & the Treaty of 1868

Sulekha Kishore, Ge136c Spring 2025

The Najavo people (also known as the *Diné*, the word the Najavo people use for themselves, meaning “The People”) are Indigenous people of the Southwestern United States (US). Today, the Navajo are the largest Native American tribe in the US and the Navajo Nation, a sovereign nation located across Arizona, New Mexico, and Utah, is the largest reservation in the US.

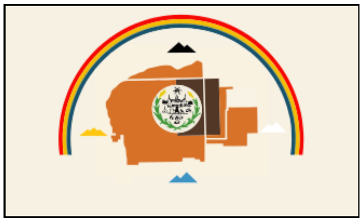


Figure 1: Flag of the Navajo Nation. Note that the dark brown area represents the reservation land ftom the 1868 Treaty

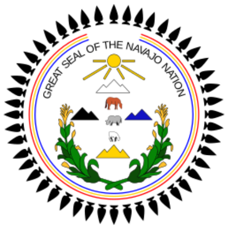


Figure 2: Seal of the Navajo Nation. The 4 Sacred Mountains represent cardinal points

America’s Indigenous People

Northeastern Arizona was occupied from 9500-5000 BCE by humans who were big game hunters. By the Archaic Period (5500 B.C.E - 300 A.D.), the people of the region shifted to maize agriculture. Sometime around 1450, the Athapaskan groups entered the Colorado Plateau, migrating from the northern sub-artic climates. **The Navajo and other Apache groups are descendants of the Athapskan.** In the harsh environment of the desert Southwest, **people lived in dispersed extended family groups or bands, planting in low-lying valleys and herding livestock** [National Park Service].

Spanish Exploration in the Southwest

Beginning in the 1600s, Spanish exploration began northward from Mexico into Arizona. **The Spanish claimed the region that the Navajo inhabited during a 1539 expedition** that passed through Arizona into New Mexico. Spanish military and clergy established outposts to enforce their claims [Arizona State Museum]. The Mexican War of Independence (1811 - 1822) resulted in a decline in exploration and Spanish activity.

American Arrival in the Southwest

The lands of Navajo became part of the US with the end of the Mexican War and the Treaty of Guadalupe Hidalgo in February 1848. As American trade and military presence increased, starting with the 1851 establishment of Fort Defiance in Arizona, so did tensions between the American military and the Navajo. **Skirmishes and killings occurred on both sides.**

Forced Removal of the Navajo

In late 1863, Col. Kit Carson and the 1st New Mexico Infantry, reoccupied Fort Canby in New Mexico and began **a scorched Earth campaign against the Navajo.** They burned homes, destroyed fields, and killed livestock. In January 1864, Carson’s troops attacked the last hold-out of Navajos, starving them before forcing them to surrender [Newell].

By mid-March 1864, **more than 6,000 Navajo people had surrendered and were forced to march over 300 miles, called the “Long Walk” by the Navajo**, across the desert to Fort Sumner in Bosque Redondo (called *Hwéeldi,* the place of suffering, by the Navajo) in eastern New Mexico. Here, the Navajo were held prisoners until 1868. Over 8,000 men, women, and children (3/4ths of the Navajo tribe) were forced on the Long Walk, with hundreds dying along the way and during the imprisonment [Newell]. **Conditions at Fort Sumner were inhuman and many were starved, raped, exploited, and killed.**

The Long Walk, 1865 - 1866

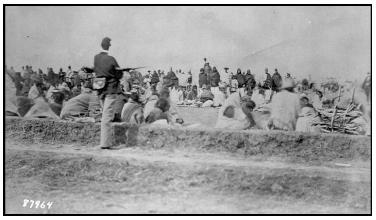
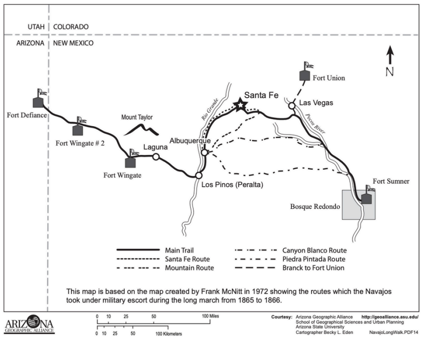


Figure 3: Fort Sumner, 1864, a U.S soldier stand gaurd over the Navajo people during the forced removal of the Navajo from their land [Wikipedia]



This map is based on the map created by Frank McNitt in 1972 showing the routes which the Navajos took under military escort during the long march from 1865 to 1866.

Courtesy: Arizona Geographic Alliance http://geoalliance.asu.edu/ School of Geographical Sciences and Urban Planning Arizona State University Cartographer Becky L. Eden NavajoLongWalk.PDF14

Figure 4: Map of the Navajo removal from Arizona to eastern New Mexico []

When the American Civil War ended in April 1865, **Congress established the Indian (so-called) Peace Commission "to establish peace with certain hostile Indian tribes,"** including the Navajos who were still in captivity at Bosque Redondo. In May 1868, two of the commissioners, **Lieut. Gen. William T. Sherman** (General of the US Army in the Civil War & future Secretary of War) and civilian **Samuel F. Tappan**, arrived at Bosque Redondo where they negotiated the Navajo Treaty of 1868.

The Treaty of 1868

Also known as the Treaty of Bosque Redondo,
to the Navajo: the Old Paper, or Naal Tsoos Sani

Americans William Sherman and Samuel F. Tappan met with Navajo leader Barboncito and 10 headsmen in May of 1868. Negotiations were exceedingly slow – words had to be translated from Navajo to Spanish then from Spanish to English – but Barbonito was a steadfast negotiator. **Sherman wanted to move the Navajo to Indian Territory (Oklahoma) while the Navajo wanted to return to their homeland.** Barbonito was resolved in the Navajo's return and Sherman later admitted that he and Tappan were **unable "to prevail on the Navajos to remove to the Indian Territory, and had to consent to their return to their former home"** [Kesell]. Defining the boundaries of the Navajo reservation was difficult – the Americans spoke of artificial lines while the Navajos of geographical features. It is unlikely that the Navajo interpreted the terms of the treaty as the Americans intended.

The 1868 treaty limited the Navajo to less than one-quarter of their original territory. The treaty has 13 articles with the preamble acknowledging the collective nature of Navajo sovereignty [Wilkins]. The articles:

- Established peace between the US and the Navajo. It also gave jurisdiction to the federal government over crimes committed by non-Navajos but the Navajo retained jurisdiction over crimes by Navajo against other Navajo.
- Gave the reservation as the exclusive domain of the Navajo.
- Was "civilization/assimilation" provision that authorized the US to build schools, chapels, and warehouses.
- Created the position of Indian agents: individuals authorized to interact with Native American tribes on behalf of the US government.
- Granted agriculture land allotments: based on the incorrect assumption that the Navajo were not already adept at farming.
- Forced Navajo children between ages 6-16 attend US schools
- Gave the right to hunt on unoccupied lands contiguous to the reservation
- The Navajo were forced to give up the right to oppose railroad construction or interfere with military fort construction

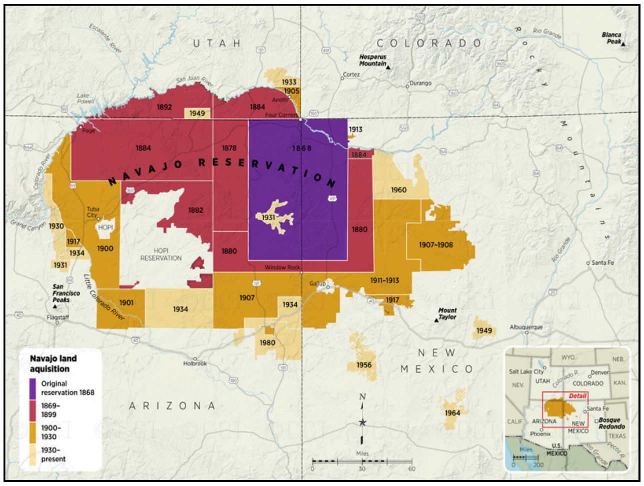
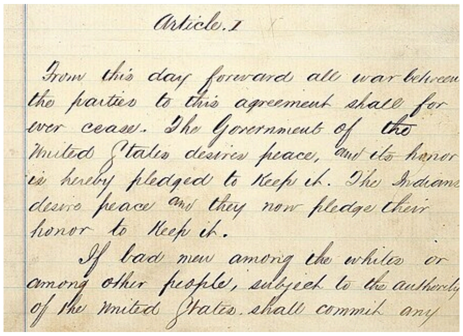

UTAH
COLORADO
ARIZONA
NEW MEXICO
NAVAJO RESERVATION
HOPI RESERVATION
HOPI
1868
1878
1880
1882
1884
1892
1900
1901
1905
1907
1907–1908
1911–1913
1913
1917
1930
1931
1933
1934
1949
1956
1960
1964
1980
Escalante River
San Juan River
Lake Powell
Page
Colorado River
Grand Canyon
Tuba City
Little Colorado River
San Francisco Peaks
Flagstaff
Holbrook
Window Rock
Gallup
Four Corners
Aneth
Cortez
Durango
Hesperus Mountain
Blanca Peak
Rio Grande
Rocky Mountains
Santa Fe
Albuquerque
Mount Taylor
Navajo land aquisition
Original reservation 1868
1869–1899
1900–1930
1930–present
Miles
0
30
60
N
WYO.
NEB.
Salt Lake City
Denver
NEV.
KAN.
Colorado R.
Detail
CALIF.
Phoenix
Bosque Redondo
TEXAS
U.S.
MEXICO
Pecos R.
200

Figure 5: Navajo Nation Land Acquisition, original land granted from the 1828 Treaty shown in purple. Credit: Smithsonian Institution, one of the several concept maps for the National Museum of the American Indian



Article 1

From this day forward all war betwee
the parties to this agreement shall for
ever cease. The Government of the
United States desires peace, and its honor
is hereby pledged to keep it. The Indians
desire peace and they now pledge their
honor to keep it.

If bad men among the whites or
among other people, subject to the authority
of the United States shall commit any

Figure 6: First page of the Treaty of Bosque Redondo. Credit: Indian Peace Commission

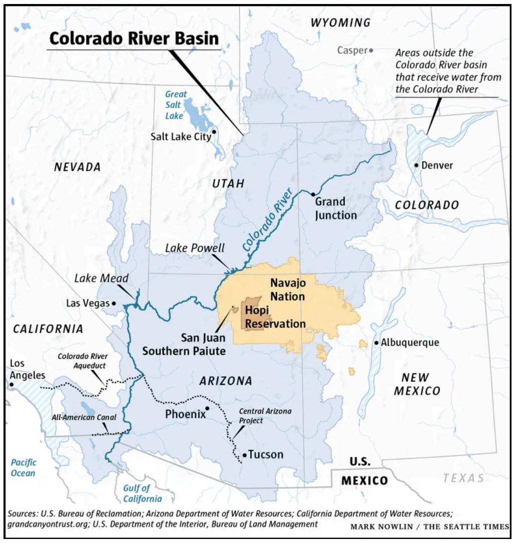

Colorado River Basin
WYOMING
Casper
Areas outside the Colorado River basin that receive water from the Colorado River
Great Salt Lake
Salt Lake City
NEVADA
UTAH
Denver
Grand Junction
COLORADO
Colorado River
Lake Powell
Lake Mead
Las Vegas
Navajo Nation
Hopi Reservation
CALIFORNIA
San Juan Southern Paiute
Albuquerque
Los Angeles
Colorado River Aqueduct
ARIZONA
NEW MEXICO
All-American Canal
Phoenix
Central Arizona Project
Tucson
Pacific Ocean
Gulf of California
U.S.
MEXICO
TEXAS
Sources: U.S. Bureau of Reclamation; Arizona Department of Water Resources; California Department of Water Resources; grandcanyontrust.org; U.S. Department of the Interior, Bureau of Land Management
MARK NOWLIN / THE SEATTLE TIMES

Figure 7: Colorado River Basin. The majority of the Navajo Nation lies within and relies on the Colorado River Basin for clean water.

Recent Developments: 1868 Treaty & Water Rights

In June 2023, the Supreme Court ruled against the Navajo Nation in *Arizona v. Navajo Nation*, in which the Navajo Nation sought for the government to identify and account for Navajo Nation water rights in the Colorado River. The 1868 Treaty includes articles with agricultural provisions and states the reservation would be the tribe's "permanent home". The Nation argued that agricultural abilities and a "permanent home" rely on water access, so the government is obligated to secure water for the tribe [Higgins]. However, in a 5-4 majority written by Justice Kavanaugh, joined by Justices Roberts, Thomas, Alito, and Barrett, the court found that the 1868 Treaty, which established the Navajo Reservation, reserved necessary water to accomplish the purpose of the Navajo Reservation **but did not require the United States to take affirmative steps to secure water for the Navajo.**

The Court emphasized that the Tribe's claims sought to compel federal action not specifically mandated by the treaty's text or established by statute, and thus fell outside the scope of enforceable obligations under federal trust responsibility. **The dissent,** led by Justice Gorsuch and joined by Justices Sotomayor, Kagan, and Jackson, **argued that the government had a duty to secure the water necessary to fulfill the treaty's promises to the Navajo people [Horkovich]. This ruling against the Navajo Nation will have drastic consequences for the tribe as their access to clean water continues to be endangered.**

Works Cited

Arizona State Museum, University of Arizona, "Culture History of Southern Arizona: Europeans Arrive." https://statemuseum.arizona.edu/online-exhibit/culture-history-southern-arizona/europeans
Higgins, Grace (2023). The Navajo Nation Fights for Water Rights in the Supreme Court. American University (Washington, D.C.); Juris Mentem Law Review. Journal contribution. https://doi.org/10.57912/23773071.v1
Horkovich, Jennifer. "Arizona v. Navajo Nation and Systemic Failures in the Tribal Water Allocation Scheme." Fordham Environmental Law Review, vol. 35, 2024.
Kessell, John L. "General Sherman and the Navajo Treaty of 1868: A Basic and Expedient Misunderstanding." The Western Historical Quarterly, vol. 12, no. 3, 1981, pp. 251–72. JSTOR, https://doi.org/10.2307/3556587.
Mapman USA, "Navajo Nation Land Acquisition Map | Oversized Custom Exhibit Map." http://www.mapmanusa.com/cci-exhibit-7.html.
National Park Service, Cultural Landscape Report: Hovenweep National Monument. http://www.nps.gov/history/history/online_books/hutr/clr/clr2a.htm.
Newell, Clayton R. "Fort Defiance, Arizona." On Point, vol. 14, no. 1, 2008, pp. 44–47. JSTOR, http://www.jstor.org/stable/26358007.
Tohe, Laura. "Hwéeldi Bééhániih: Remembering the Long Walk." Wicazo Sa Review, vol. 22, no. 1, 2007, pp. 77–82. JSTOR, http://www.jstor.org/stable/30131304. Accessed 22 May 2025.
Wilkins, David E. The Navajo Political Experience. 4th ed., Rowman & Littlefield, 2013

Anna Kitagawa
Ge 136c

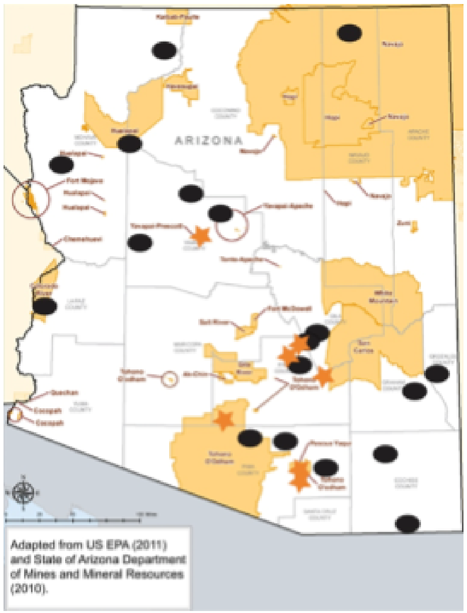
Copper Mining in Central Arizona: Tailings, Toxins, and Remediation

1. Introduction & Regional Context

Central Arizona lies at the heart of the nation's copper industry. Arizona produces roughly 65 percent of U.S. copper, with 27 major mines (Superfund Research Center, 2020). These open-pit mines extract and crush massive ore bodies, then process them via various methods to concentrate copper (EPA, 2025). The most relevant methods include leaching and smelting.

Over time, this production has generated massive amounts of waste, or tailings, including sulfuric acid and metals/metalloids (U.S. DOI). The release of these harmful substances present both environmental challenges and remediation opportunities.

Many mines are located on tribal lands (Superfund Research Center, 2020). This has put indigenous populations at a higher risk of chronic health conditions as a result of their exposure to poor air quality and contaminated water. Major mines are marked with black ovals and orange stars (major mines on tribal lands) on the map to the right.



Adapted from US EPA (2011) and State of Arizona Department of Mines and Mineral Resources (2010).

Superfund Research Center, 2020.

2. Tailings Generation & Management

In the leaching process, acids are added to copper ore in order to dissolve the copper (EPA, 2025). The copper can then be extracted from this solution. When not properly contained, this leaching process can release heavy metals into groundwater or surface water, resulting in environmental damage.

For smelting, ore is heated and then separated (EPA, 2025). This results in a large quantity of slag. After milling or heap-leaching of copper ore, the residual rock particles—tailings—remain suspended in water as a slurry. In Arizona's arid climate, tailings impoundments are engineered to maximize water recovery: as solids settle, "reclaim" water is returned to processing, reducing freshwater withdrawals (EPA, 2010). Impoundments are raised over time using upstream, centerpoint, or downstream dam-raising methods; each carries differing stability and seepage risks.

The state has accumulated an estimated 17.5 billion tons of copper tailings since the late 19th century (AZ Board of Regents, 2023). These fine, sand-sized particles remain susceptible to wind dispersion and erosion, necessitating ongoing maintenance of impoundment dams, seepage control systems, and dust-suppression measures.

3. Toxins & Environmental Impacts

The oxidation of sulfide minerals in tailings generates sulfuric acid, a process known as acid rock drainage. The acid used to dissolve the copper also dissolves other heavy metals—lead, arsenic, uranium, and others—which may then be accidentally released into surface streams and shallow aquifers (EPA, 2025). The EPA's Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) program highlights that tailings may concentrate radionuclides like uranium and radium, which leach more readily under acidic conditions.

Surface-water impacts are also significant. Seepage and stormwater runoff from tailings facilities have led to elevated copper and acidity levels in streams such as in 2011 when a pipeline rupture released acidic solution into the watershed, resulting in fines and operational changes at Morenci Mine (U.S. DOI).

According to Earthworks, 100% of the mines they looked at experienced pipeline spills or other accidental releases, and 92% had water collection/treatment systems that failed to control seepage (Earthworks, 2012). Releases such as these have impacted migratory birds, as well as their support ecosystems. These damages have resulted in legal action being taken against mines.

4. Remediation & Reclamation Strategies

Regulatory Framework: The Arizona Department of Environmental Quality oversees both active-mine permit compliance (via the Aquifer Protection Permit program) and legacy mine remediation under its Legacy Mines Program (ADEQ, 2025). Federal oversight can include Superfund listings for the most contaminated sites, requiring long-term monitoring and community engagement.

Engineering Controls: Mines often recycle their water to minimize discharges of wastewater (EPA, 2010). In order to prevent discharges, mines may construct berms to redirect precipitation back into the mining area rather than releasing into the surrounding area.

Passive & Natural Treatment: Soil capping and rainwater capture may be able to support revegetation in mined areas to counteract the damage from waste rock dumps and mine tailings (Superfund Research Center, 2020).

Research Frontiers: University of Arizona Superfund researchers and industry partners are exploring tailings reprocessing to recover residual copper and critical minerals, transforming waste into an economic resource while reducing long-term liability (AZ Board of Regents, 2023).

5. Conclusion & Future Outlook

Copper mining underpins Arizona’s economy but leaves a legacy of tailings, toxins, and complex remediation challenges. Balancing resource recovery with environmental stewardship requires continued innovation in tailings dewatering, in situ treatment, and waste-reprocessing technologies. Strengthened regulations, community engagement, and public–private research collaborations will be critical to transforming copper mining waste from an environmental burden into a sustainable industrial asset.

6. References

Copper mining in AZ and Tribal Lands. Superfund Research Center. (2020, July 13). https://superfund.arizona.edu/resources/modules/copper-mining-and-processing/copper-mining-az-and-tribal-lands

Earthworks. (2012, July). *U.S. Copper Porphyry Mines Report*. https://www. earthworksaction.org

Mining Arizona’s hidden treasure. Mining Arizona’s hidden treasure | Arizona Board of Regents. (2023, September 28). https://azregents.edu/news-releases/mining-arizonas-hidden-treasure

Morenci mine - Phelps Dodge Industrial Mining Complex. US Department of the Interior. (n.d.). https://www.cerc.usgs.gov/orda_docs/CaseDetails?ID=1024

Surface Water Quality Remediation Sites. Arizona Department of Environmental Quality. (2025, May 16). https://www.azdeq.gov/legacymines

United States Environmental Protection Agency. (2025, March 26). *TENORM: Copper Mining and Production Wastes*. EPA. https://www.epa.gov/radiation/tenorm-copper-mining-and-production-wastes

United States Environmental Protection Agency. (2010, March). *Site Visit Report Arizona Copper Mines.* EPA. https://www.epa.gov

Jarek Kwiecinski
Ge 136c Report (Packrat middens)

Figure 1: A desert packrat hiding in an agave plant.

Packrats (*Neostema* sp.) are rodents that are most abundant in the western United States and Northern Mexico. They are roughly the size of brown rats, the dominant rat species in most cities around the world. Packrats assemble twigs and other plant materials to construct elaborate nests, or middens, often in caves or rock crevices. In deserts, packrats may construct their middens around or within clumps of prickly pear or cholla cacti for protection against predators. They can also become a nuisance in rural areas where the will inhabit attics or even car engines, causing significant destruction (1). Like many rodents, packrats can become infested with fleas that carry *Yersinia pestis*, the bacterium responsible for the bubonic plague. Because of this, there are still a few plague cases in the desert southwest each year (2). Packrats can also become infected with the Sin Nombre Virus, the causative agent of the often-fatal hantavirus pulmonary syndrome which first occurred in the Four Corners region in 1993. Some studies suggest that packrats are a dead-end host for this virus, unable to continue its transmission. However, because other rodents which do transmit the virus often use pack rat middens for shelter, it is important to use caution when handling midden debris (3).

Packrat middens are of interest to paleoclimatologists because the plant materials trapped within can be preserved for tens of thousands of years. This preservation is enabled in part by the material properties of packrat urine, which is highly viscous and forms a cement-like material (known as amberat) when dried. Since many middens are also sheltered from the elements, the plant remains contained within can be preserved with exquisite detail, allowing for the range of different plant species to be reconstructed over time. The oldest known middens have a radiocarbon age of 50,000 years, so this record provides information about plant species distributions for about half of the last glacial period and all of the Holocene. Such information is useful in understanding past climate because the diverse plant species of the Southwest have very different temperature and precipitation requirements. Today, valley floors are dominated by bunchgrasses or creosote shrubs, with saguaro cacti appearing in parts of the Sonoran desert in Arizona and Mexico. According to packrat midden data, these species were restricted to the absolute lowest elevations near Death Valley and in parts of southwestern Arizona during the last ice age. Most valley floors were instead occupied by piñon-juniper woodlands, a vegetation type that is now restricted to moderate elevations (6000-8000 ft or 1800-2400 m) of the region’s mountains. Finally, large swaths of the southwest were once covered by mixed conifer forest, containing Douglas-fir and

Figure 2: Piñon-juniper woodland in central New Mexico.

white fir at lower elevations and Engelmann spruce, subalpine fir, and Rocky Mountain bristlecone pine at higher elevations. These forests still exist at the highest elevations (8000-12000 ft or 2400-3700 m) of most mountain ranges in New Mexico, some of which still reach above treeline. They can also be found atop Arizona's San Francisco Peaks and in higher elevations of the Mogollon Rim, a plateau stretching from Flagstaff to the Mogollon Mountains in southwestern New Mexico. Finally, the ponderosa pine, today a species that is widespread throughout the Mogollon Rim and much of the mountain west, appeared in the region only after glaciation (4).

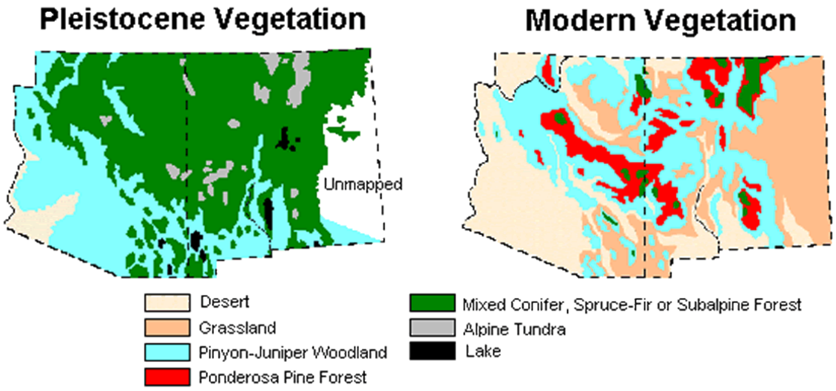


Figure 3: Overview of shifts in vegetation patterns throughout the Southwestern US since the Last Glacial maximum. In addition to plant community changes, note the several large Pleistocence lakes that disappeared through this climatic shift (4).

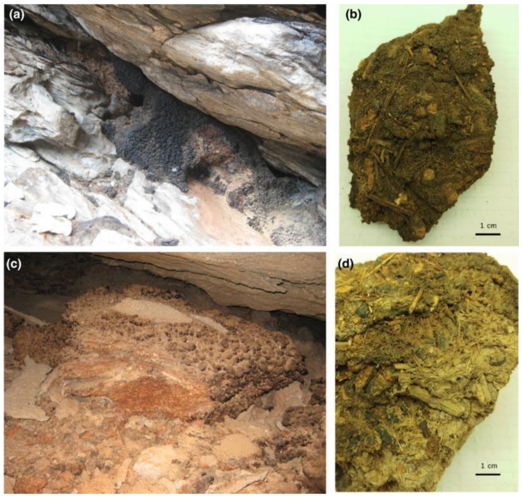


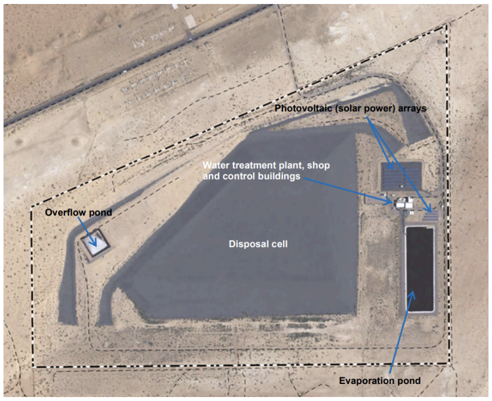
Figure 4: Two fossilized packrat middens, with fossils magnified on the right (5).

Packrat middens also preserve ancient DNA, enabling more detailed ecological reconstructions. Samples must be handled with extreme care to prevent modern DNA contamination and the degradation of ancient DNA. Amongst plants, DNA has been assigned to taxa at the family level, so shifts between grasses (Poaceae), the clade containing pines, firs, and spruces (Pinaceae), and junipers (Cupressaceae) have been identified (5). Though much of this information can be obtained from macrofossils, small insects and prokaryotes do not leave identifiable fossils in middens, so metagenomics is a promising approach to study these taxa. Researchers have even identified insects in middens at the species level (6). Overall, this technique is emerging as an alternative to fossil identification, which requires specialized training that few now possess.

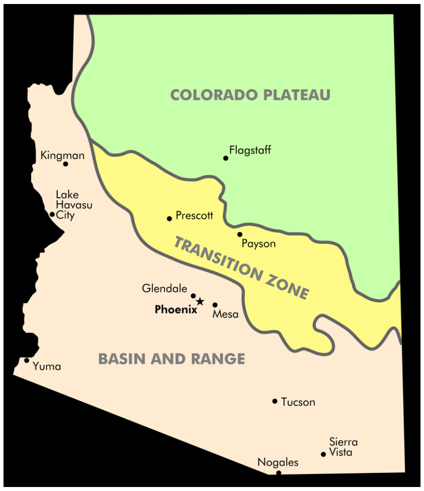
References: **1.** USGS (2022). https://www.usgs.gov/centers/geosciences-and-environmental-change-science-center/science/usgs-north-american-packrat. **2.** CDC (2024).https://www.cdc.gov/plague/about/index.html. **3.** R. Feuer, et al. J Virol **73**, 9544–9554 (1999). **4.** C. Allen, et al., "Landscape changes in the southwestern United States: Techniques, long-term datasets, and trends: Chapter 9" (1998-0003-p, U.S. Geological Survey, 1998); https://pubs.usgs.gov/publication/70180831. **5.** G. Moore, et al. *Ecol Evol* **10**, 2530–2544 (2020). **6.** A. D. Smith, et al. *Sci Rep* **11**, 12635 (2021).

Nuclear Waste Storage in Arizona – Tuba City

Donny Lu


Photovoltaic (solar power) arrays
Water treatment plant, shop and control buildings
Overflow pond
Disposal cell
Evaporation pond

Tuba City Disposal Site, located approximately 85 miles northeast of Flagstaff, Arizona, is one of three principal nuclear waste storage sites in the state. Originally operated as a uranium mill from 1956 to 1966, the site was converted into a long-term radioactive waste disposal facility in 1978 under the *Uranium Mill Tailings Radiation Control Act (UMTRCA)*.


COLORADO PLATEAU
Kingman
Flagstaff
Lake Havasu City
Prescott
Payson
TRANSITION ZONE
Glendale
Phoenix
Mesa
Yuma
BASIN AND RANGE
Tucson
Sierra Vista
Nogales

Arizona's geographic setting can be divided into three main physiographic provinces: the **Colorado Plateau**, the **Transition Zone**, and the **Basin and Range Province**. Tuba City is situated within the Colorado Plateau—a region characterized by broad, high-elevation plateaus and relatively stable sedimentary rock layers. In contrast, Prescott and Sedona lie within the Transition Zone, a geologically complex and rugged mountainous belt along the **Mogollon Rim**, which separates the plateau from the lower desert basins to the south.

Geological Stability

Geographically, the Tuba City area is underlain by thick, relatively **stable sedimentary formations**. The waste site sits on an alluvial terrace underlain by the **Navajo Sandstone**, a massive sandstone formation that forms a regionally extensive aquifer. Above the bedrock are thin layers of dune sand and gravel. The Colorado Plateau is an old, structurally stable craton with relatively **low seismic activity.**

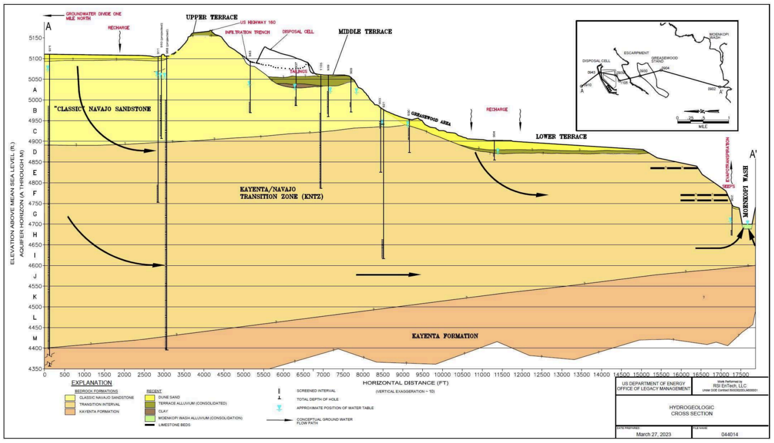
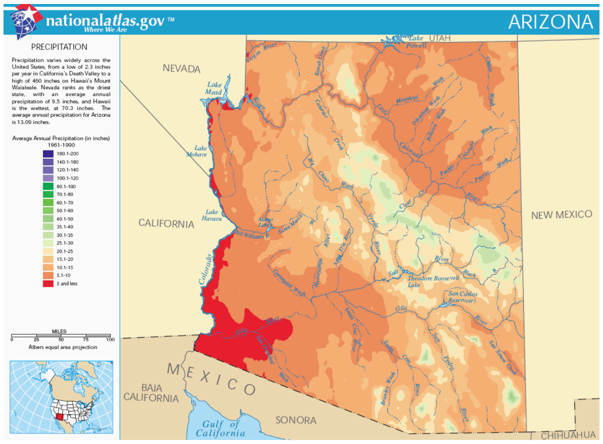

GROUNDWATER DIVIDE ONE MILE NORTH
A
RECHARGE
UPPER TERRACE
US HIGHWAY 160
INFILTRATION TRENCH
DISPOSAL CELL
MIDDLE TERRACE
TAILINGS
"CLASSIC" NAVAJO SANDSTONE
GREASEWOOD AREA
RECHARGE
LOWER TERRACE
KAYENTA/NAVAJO TRANSITION ZONE (KNTZ)
EVAPOTRANSPIRATION
SEEPS
MOENKOPI WASH
A'
KAYENTA FORMATION
ELEVATION ABOVE MEAN SEA LEVEL (ft.)
AQUIFER HORIZON (A THROUGH M)
HORIZONTAL DISTANCE (FT)
(VERTICAL EXAGGERATION ~ 10)
EXPLANATION
BEDROCK FORMATIONS
CLASSIC NAVAJO SANDSTONE
TRANSITION INTERVAL
KAYENTA FORMATION
RECENT
DUNE SAND
TERRACE ALLUVIUM (CONSOLIDATED)
CLAY
MOENKOPI WASH ALLUVIUM (CONSOLIDATION)
LIMESTONE BEDS
SCREENED INTERVAL
TOTAL DEPTH OF HOLE
APPROXIMATE POSITION OF WATER TABLE
CONCEPTUAL GROUND WATER FLOW PATH
ESCARPMENT
GREASEWOOD STAND
MOENKOPI WASH
MILE
US DEPARTMENT OF ENERGY OFFICE OF LEGACY MANAGEMENT
Work Performed by RSI EnTech, LLC
HYDROGEOLOGIC CROSS SECTION
DATE PREPARED: March 27, 2023
FILE NAME: 044014

Figure 4. Tuba City Site Hydrogeologic Cross Section and Vertical Horizon Discretizations

Groundwater and Hydrology

The **depth to groundwater** is around 60–75 feet below the surface at the site . Beneath the site, the Navajo Sandstone hosts the main regional aquifer (sometimes called the "Navajo aquifer"), which is **thick (~500 feet saturated thickness)** near the site . Importantly, this aquifer thins out and discharges toward Moenkopi Wash a short distance south of the site, meaning groundwater flow carries any contaminants toward the wash and the Little Colorado River (away from populated areas). As compare to the Prescoot region where groundwater is considered a critical and limited resource to the community, there is *no known use of groundwater* directly in the contaminated plume region near Tuba city; local residents get their water from wells in the bedrock aquifer further away . In other words, at Tuba City the groundwater is relatively deep and regional, and the population does not depend on shallow water near the cell – reducing the risk of exposure .

Climate and Aridity

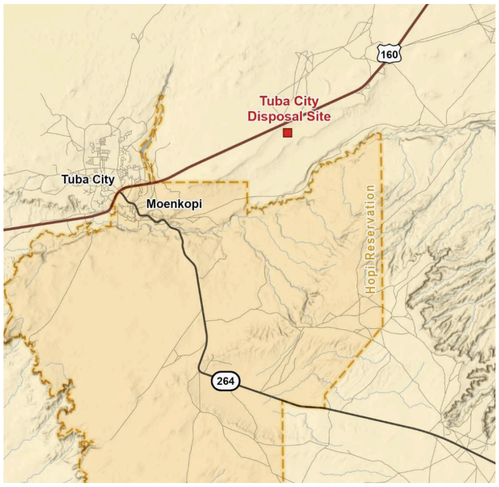

nationalatlas.gov™
Where We Are
ARIZONA
PRECIPITATION
Average Annual Precipitation (in inches) 1961-1990
180.1-200
140.1-180
120.1-140
100.1-120
80.1-100
70.1-80
60.1-70
50.1-60
40.1-50
35.1-40
30.1-35
25.1-30
20.1-25
15.1-20
10.1-15
5.1-10
5 and less
MILES
0
25
50
75
100
Albers equal area projection
NEVADA
UTAH
CALIFORNIA
NEW MEXICO
MEXICO
BAJA CALIFORNIA
SONORA
CHIHUAHUA
Gulf of California
Lake Mead
Lake Mohave
Lake Havasu
Theodore Roosevelt Lake
San Carlos Reservoir

Precipitation varies widely across the United States, from a low of 2.3 inches per year in California's Death Valley to a high of 460 inches on Hawaii's Mount Waialeale. Nevada ranks as the driest state, with an average annual precipitation of 9.5 inches, and Hawaii is the wettest, at 70.3 inches. The average annual precipitation for Arizona is 13.09 inches.

One of the most decisive advantages of Tuba City's location is its **dry climate**. Tuba City is located in the **desert-steppe climate** of the Colorado Plateau's western edge, with an average annual precipitation of only **~6.4 inches** . Most years see very little rain; for example, some months receive well under half an inch on average . This aridity greatly reduces the amount of water that can percolate through soil or rock to mobilize contaminants. Less rainfall means less leachate generation in a waste repository and a **lower probability of erosion or flooding**.

Transportation and Infrastructure

Even though Tuba City is remote, it is accessible by significant road infrastructure, which was a factor during the remediation project. U.S. Highway 160 runs just north of the disposal site, and U.S. 89 is nearby, connecting the area to Interstate 40 at Flagstaff. During the late 1980s cleanup, equipment and materials could be trucked to the Tuba City site via these highways without crossing through dense urban centers. The original uranium ore was hauled to the mill via these routes as well, indicating the roads can handle heavy loads. Rail transport is not available right to Tuba City, but the relatively direct highway route meant that hauling 800,000 tons of tailings into the on-site cell was feasible over a short distance (in fact, much of it was moved just a few hundred yards from the old tailings piles into the new lined cell).


160
Tuba City Disposal Site
Tuba City
Moenkopi
Hopi Reservation
264

This does not imply that Tuba City is a "perfect" site – challenges remain, such as groundwater contamination that is being actively remedied and the need for perpetual monitoring given the 1,000-year design lifespan of the cell. However, relative to other locations in Arizona, it was one of the *most* suitable choices available and has successfully contained over 1.1 million cubic meters of radioactive mill tailings in a 50-acre engineered cell.

References:

1. U.S. Nuclear Regulatory Commission (2024). Arizona Geological Suitability for Spent Fuel Storage and Repository Development.. Retrieved from https://www.nrc.gov/docs/ML2431/ML24319A122.pdf

2. U.S. Department of Energy, Office of Legacy Management. (n.d.). Tuba City, Arizona, Disposal Site Fact Sheet. Retrieved May 2025, from https://www.energy.gov/lm/articles/tuba-city-arizona-disposal-site-fact-sheet

3. Arizona Statewide Data Network (n.d.). Geography of Arizona. Retrieved from https://asdn.net/ngc2007/include/geography.htm

4. U.S. Department of the Interior, National Atlas Program. (n.d.). National Atlas of the United States. Retrieved from https://nationalatlas.gov

5. WISE Uranium Project. (n.d.). U.S. Uranium Mill Tailings Sites – Groundwater Contamination and Compliance Data. Retrieved from https://www.wise-uranium.org/udusat1.html

Cholla Power Plant: Long Term vs Short Term Benefits

America Luna Herrera **May 25, 2025**

Introduction

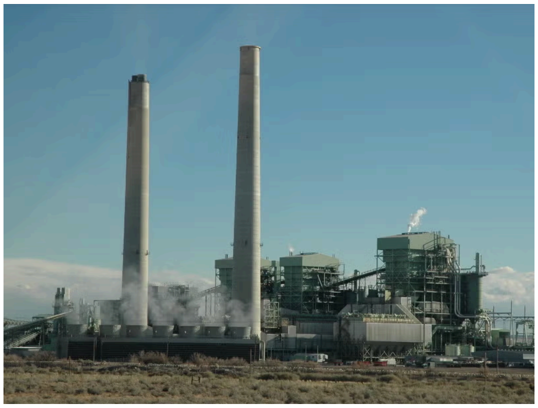


Figure 1. Cholla Coal Power Plant in Joseph City, Arizona.

The Cholla Power Plant was one of three major coal power plants in Arizona. It is located in Joseph City, Arizona and used to operate four units. The first three units are owned by Arizona Public Services (APS) and the fourth by Pacificorp. The first unit was commissioned in 1962.

In March 2025, the Cholla Power Plant was shut down. Historically, coal has been a significant energy source in Arizona, and many believed it would remain viable well into the future. Yet, the decision to shut down the Cholla Power Plant was up for consideration for years, driven by environmental regulations and aging infrastructure.

The plant was crucial for the Joseph City community, providing over 350 jobs [3]. While the shutdown is an environmental policy milestone, it also shows the complexity of shifting to cleaner energy.

Background

The Cholla Power Plant was built in phases through the 1970s. The four units together could generate up to 1.02 gigawatts of electricity. Millions of tonnes of coal were burned annually, first supplied by the McKinley coal mine, and after 2010, by the Lee Ranch and El Segundo mines, all located in New Mexico [4].

In a typical coal-fired power plant, the process begins with the pulverizing coal into a fine powder. In this state, the coal is more combustible. This powdered coal is then burned in a boiler, creating high-temperature steam. The steam, under extreme pressure, has enough force to rotate turbine blades. The connected rotating turbine spins an electromagnet inside copper coils in a generator. This produces electricity. After passing through the turbine, the steam is condensed back into water and returned to the boiler to repeat the cycle [6].

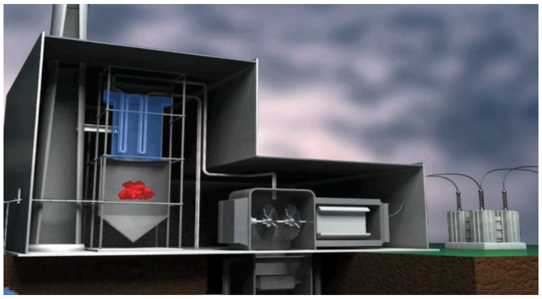
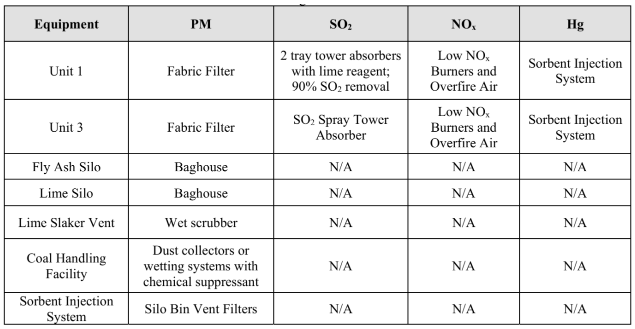


Figure 2. Process of coal-fired power plant.

Cholla Power Plant used Cholla Lake as a cooling pond to absorb the heat produced from generating electricity, while additional retention and sedimentation ponds collected wastewater and surface runoff to reduce environmental contamination [4]. To meet federal air pollution regulations, Cholla implemented a range of pollution control systems. Fabric filter baghouses captured over 99% of particulate matter. Lime-based absorbers removed sulfur dioxide, while low-NOX burners and overfire air systems limited nitrogen oxide formation. Sorbent injection systems handled mercury emissions by trapping mercury before it left the stack [2].



Equipment	PM	SO_2	NO_x	Hg
Unit 1	Fabric Filter	2 tray tower absorbers with lime reagent; 90% SO_2 removal	Low NO_x Burners and Overfire Air	Sorbent Injection System
Unit 3	Fabric Filter	SO_2 Spray Tower Absorber	Low NO_x Burners and Overfire Air	Sorbent Injection System
Fly Ash Silo	Baghouse	N/A	N/A	N/A
Lime Silo	Baghouse	N/A	N/A	N/A
Lime Slaker Vent	Wet scrubber	N/A	N/A	N/A
Coal Handling Facility	Dust collectors or wetting systems with chemical suppressant	N/A	N/A	N/A
Sorbent Injection System	Silo Bin Vent Filters	N/A	N/A	N/A

Table 1. Air pollution control technologies used at the Cholla Generating Station. Source: https://static.azdeq.gov/pn/aq_aps_cholla_tsd.pdf

Yet, as the plant aged and regulatory demands increased, it became expensive to maintain the plant. Unit 2 was retired in 2015, unit four in 2020, and the final two by March 2025.

Environmental Concerns

In Arizona, for decades, Cholla was one of the largest sources of air pollution. The coal combustion process releases significant amounts of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and mercury [7]. These all contribute to acid rain, respiratory illnesses, lung disease and other health concerns [1]. The plant also emitted millions of tons of carbon dioxide annually, making it a major contributor to climate change. The issue is greater Cholla. In 2022, coal burning was responsible for 19% of all carbon dioxide emissions in the United States.

Coal power plants also raise concerns about water usage. Power plants often damage local ecosystems by withdrawing large volumes of groundwater for cooling and releasing heated water back into the environment.

Because of these significant long-term consequences, environmentalists urge a transition to renewable energy.

Trump Administration

President Trump has signed a few executive orders to encourage the continuation of coal-power plants. He argues that the coal industry is essential to the United States. These efforts are meant to conserve American jobs and expand American energy sources. The Trump Administrations believes that there will be a rising demand to power artificial intelligence data centers [8].

Environmentalists have spoken out against this approach. [9][10]

Conclusion

The Cholla Power Plant shutdown was both tragic and inevitable. Generations of Joseph City residents worked at Cholla, and it was central to their town identity. It is expected that schools, public services, and small businesses will be affected. APS and state officials have promised to support the community.

Coal-fired plants are becoming more and more outmatched by cheaper, cleaner energy sources like solar and natural gas. Even with President Trump's 2025 clean-coal executive orders, it is hard to justify the maintenance of coal plants. Cholla emitted millions of tons of carbon dioxide, consumed vast quantities of groundwater, and left behind toxic coal ash.

Communities like Joseph City will need to rebuild.

References:

1) Acken, A. H., & Bingham, M. G. (2011). Sustainable energy in Arizona. Arizona State Law Journal, 43(3), 673–730. Retrieved from https://heinonline.org/HOL/Page?handle=hein.journals/arzjl43&div=31&g_sent=1&casa_token=&collection=journals
2) Arizona Department of Environmental Quality. (n.d.). Technical review and evaluation of application for air quality permit No. 92117. Retrieved from https://static.azdeq.gov/pn/aq_aps_cholla_tsd.pdf
3) Bryan, S. M. (2025, May 5). Arizona communities bank on Trump's push for coal to ensure they're not forgotten. The Columbian. Retrieved from https://www.columbian.com/news/2025/may/05/arizona-communities-bank-on-trumps-push-for-coal-to-ensure-theyre-not-forgotten/

4) NS Energy. (n.d.). Cholla Power Plant, Arizona. Retrieved May 25, 2025, from https://www.nsenergybusiness.com/projects/cholla-power-plant-arizona/

5) Smith, S. T. (1976). Power generation in Arizona and its environmental implications (Master's thesis, University of Arizona). Retrieved from https://repository.arizona.edu/bitstream/handle/10150/566551/AZU_TD_BOX287_E9791_1976_21.pdf?sequence=1

6) Tennessee Valley Authority. (2025). How a coal plant works. Retrieved May 25, 2025, from https://www.tva.com/Energy/Our-Power-System/Coal/How-a-Coal-Plant-Works

7) U.S. Environmental Protection Agency. (2017, January). Cholla Power Plant SO_2 DRR Modeling Report. Retrieved from https://www.epa.gov/sites/default/files/2017-01/documents/cholla-so2_drr_modeling_report.pdf

8) The White House. (2025, April). Fact Sheet: President Donald J. Trump Reinvigorates America's Beautiful Clean Coal Industry. Retrieved from https://www.whitehouse.gov/fact-sheets/2025/04/fact-sheet-president-donald-j-trump-reinvigorates-americas-beautiful-clean-coal-industry/

9) Wiles, R. (2025, April 9). Trump: Keep APS's Cholla Power Plant open to boost 'beautiful, clean coal industry'. The Arizona Republic. Retrieved from https://www.azcentral.com/story/money/business/energy/2025/04/09/trump-wants-to-keep-aps-cholla-power-plant-open/83000833007/

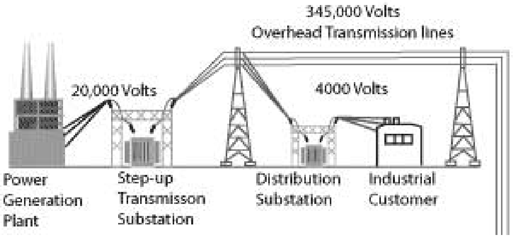
10) Wiles, R. (2025, April 24). Trump gives Arizona coal plant, among others, 2 extra years to meet tougher regulations. The Arizona Republic. Retrieved from https://www.azcentral.com/story/money/business/energy/2025/04/24/apache-coal-plant-arizona-two-years-to-meet-new-regulations/83231486007/

Nuclear Power in AZ

Mark Gherghetta

Generating Electricity

In a world where electricity consumption continues to grow, power generation remains a vital organ that fuels any modern society. There are many methods of generating electrical energy that involve using other forms of energy. The largest is through the burning of fossil fuels (oil, natural gas, coal) which accounts for 60% of the total electricity production in the United states. The second largest is through the use of renewable energy (wind, solar, hydropower) which accounts for ~21% of the US electricity production. The remaining electricity is generated from nuclear power which proves to be a safe and sustainable power generation method.



Nuclear Power

Nuclear power relies on the energy stored inside the nucleus of the atom. Such processes of harnessing that energy are nuclear fission, nuclear fusion, and nuclear decay. Most nuclear power plants rely on nuclear fission of uranium and plutonium for electricity generation. Neutrons collide with these atoms and split them which releases large amounts of heat. These reactions are controlled through various cooling methods and neutron absorbers to prevent the reaction from getting out of control. The heat generated from this reaction is used to generate steam which then turns a turbine that generates electricity. A power plant will output a high voltage which then gets stepped up and sent through overhead transmission lines before being stepped down and distributed to customers.

Development of Nuclear Plants in Arizona

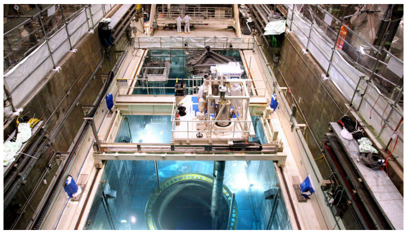
Today, Arizona contains one major nuclear power plant: the Palo Verde Generating Station. The station was originally planned in the 1970s. At the time of its planning, people were skeptical about the site: a patch of desert land 50 miles west of Phoenix with no natural water reservoir nearby and in an area with prevailing winds. Despite these concerns, construction commenced and the station was completed. As its water source, the site treated sewage water from nearby cities. Its first two reactors began service in 1986 and the third reactor began service in 1988. In 2005 the 3 reactors were upgraded which increased the electric power output capacity. As of today, the plant is under operation by APS (Arizona Public Service) with a lease that is set to expire in the late 2040s. No other nuclear reactors are located in Arizona, with the University of Arizona reactor being retired in 2012.

Palo Verde Generating Station

The Palo Verde Generating Station (located near Tonopah, AZ) is the largest power plant in the United States by net electricity output. Its three pressurized-water reactors (each roughly 1.4 GW after power upgrades total about 3,937 MW capacity. Annually, Palo Verde produces on the order of 32 million megawatt-hours (MWh) of electricity which is roughly one-third of Arizona's total electricity generation. Palo Verde's 500 kV switchyard connects into the Western grid via multiple transmission lines, so its power is shared with neighboring states including density populated urban centers such as Albuquerque, New Mexico; Las Vegas, Nevada; and even Los Angeles and San Diego.

Environmental Impacts

As mentioned, nuclear power is sustainable, unlike other methods of electricity generation. In particular, the Palo Verde nuclear plant emits virtually no carbon dioxide or combustion pollutants at all throughout the process. Through the lifetime of its production, Arizona Public Service estimates that the Palo Verde station has avoided 500 million metric tons of CO_2 emission compared to equivalent output from a fossil fuel generator. Essentially, all of the electricity is carbon free, and the plant supplies 70% of Arizona's clean electricity without direct greenhouse gas emissions. The smoke you generally see coming out of a nuclear plant is just steam.



Additionally, Palo Verde uses recycled water. Generally nuclear plants are built near a large body of water so they can use it for cooling. These plants then directly take the water from those bodies of water which have a direct impact on their ecosystems. However, the Palo Verde plant intakes about 23-26 billion gallons of treated sewage water from the Phoenix metropolitan area each year. Recycling water this way is a tremendous resource saver.

While the facility has a positive environmental impact in allocation of water, the facility produces lots of radioactive waste. Nuclear fuel assemblies are replaced every 18 months, but still contain lots of highly radioactive material. They generally store this waste underwater as a way of shielding the radiation.

Economic Impacts

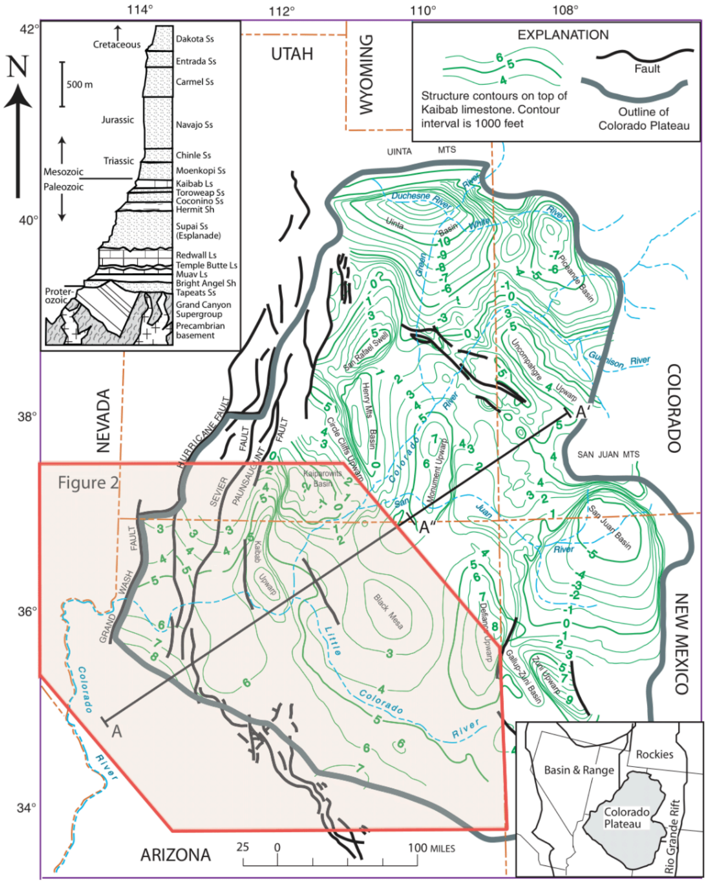
The Palo Verde station is also a major economic asset. The plant itself generates ~32 million MWh of electricity output, supplying about a third of Arizona's entire electricity. This large, reliable baseload generation supports the state's economy and helps stabilize the regional grid. Because nuclear fuel is energy-dense, Palo Verde can generate gigawatts continuously (24/7), buffering against price spikes from more intermittent or fuel-price-sensitive sources. The creation of the plant has also directly led to the creation of thousands of jobs and it is one of the region's largest employers. Production costs for the facility are low as nuclear power has high upfront capital costs but low operating and fuel costs

Future Outlook

Looking at the future outlook, Palo Verde itself is aging while Arizona's utilities explore new nuclear options. All three reactors reached their 40th anniversary around 2026, and their current NRC licenses expire in the mid-2040. APS plans to seek another 20-year renewal to extend operation into the 2060s, however, no new units are planned at the site. While the nuclear power landscape in Arizona lies primarily in the hands of the Palo Verde station, Arizona's largest utilities have signaled interest in adding new reactors elsewhere. In 2023 APS, SRP and Tucson Electric applied for DOE funding to study small modular reactors (SMRs) or advanced designs and to identify candidate sites. The utilities estimate that, if funded, site selection could occur by the late 2020s, with construction of new nuclear units possibly in the 2030s and operation in the early 2040s. These proposed SMRs would be much smaller (hundreds of MW) than Palo Verde's units, and any project would need community and regulatory approval. Meanwhile, Arizona's long-term energy plans (including pending renewable energy goals) will shape how nuclear competes or complements solar, wind, and storage.

Sources:

1. https://www.osha.gov/etools/electric-power/illustrated-glossary/power-generation-plant
2. https://www.maricopa.gov/1002/PVGS
3. https://news.azpm.org/p/news-splash/2017/5/10/110289-inside-arizonas-only-nuclear-power-plant/
4. https://www.srpnet.com/grid-water-management/grid-management/power-generation-stations
5. https://www.abc15.com/news/local-news/investigations/heres-why-more-nuclear-plants-could-be-coming-to-arizona


114°
112°
110°
108°
42°
40°
38°
36°
34°
N
500 m
Cretaceous
Jurassic
Triassic
Mesozoic
Paleozoic
Proterozoic
Dakota Ss
Entrada Ss
Carmel Ss
Navajo Ss
Chinle Ss
Moenkopi Ss
Kaibab Ls
Toroweap Ss
Coconino Ss
Hermit Sh
Supai Ss (Esplanade)
Redwall Ls
Temple Butte Ls
Muav Ls
Bright Angel Sh
Tapeats Ss
Grand Canyon Supergroup
Precambrian basement
UTAH
WYOMING
EXPLANATION
Structure contours on top of Kaibab limestone. Contour interval is 1000 feet
Fault
Outline of Colorado Plateau
UINTA MTS
COLORADO
NEW MEXICO
NEVADA
ARIZONA
SAN JUAN MTS
Figure 2
HURRICANE FAULT
SEVIER FAULT
PAUNSAUGUNT FAULT
GRAND WASH FAULT
Uinta Basin
Duchesne River
Green River
White River
Piceance Basin
Gunnison River
Uncompahgre Upwarp
San Rafael Swell
Henry Mts Basin
Circle Cliffs Upwarp
Monument Upwarp
Kaiparowits Basin
Kaibab Upwarp
Black Mesa
San Juan Basin
Defiance Upwarp
Gallup-Zuni Basin
Zuni Upwarp
Little Colorado River
Colorado River
A
A'
A''
25
0
100 MILES
Basin & Range
Rockies
Colorado Plateau
Rio Grande Rift

Mogollon Rim Uplift

Mira Menezes

The Mogollon rim is the southwest boundary of the Colorado plateau. Over the last 80-90 million years, the Colorado plateau has been uplifted by 2km with respect to the rest of the continent. How this 30-45km deep block of crust was uplifted in one piece is still somewhat unclear. This escarpment reveals sedimentary formations deposited from the Cambrian until the Carboniferous, often shared with the Grand Canyon and other sites. There is evidence that there have been multiple periods of uplift for the Colorado plateau to get to where it is now, and so this uplift likely has many related causes.

For most of the Paleozoic and Mesozoic, the Colorado Plateau was below sea level, accumulating sediments and featuring some of the amazing fossils found today. Beginning in the late Cretaceous (70-90Ma), the subducting Farallon plate experienced flat-slab subduction, when the oceanic lithosphere stayed parallel and directly underneath the continental lithosphere for hundreds of miles. This shallow Laramide slab created great friction, slab material, and water and drove contraction and vulcanism in the basin and range province. Many theories seek to explain how this ongoing flat-slab subduction also drove uplift of the Colorado plateau.

Today, most submarine crust is thin, otherwise buoyancy would push it up above sea level. Assuming that the colorado plateau crust also used to be relatively thin, if it became thicker this could account for the uplift. As the Laramide slab moved eastwards, it was accompanied by an eastward moving strain front. At the same time, water from the slab and other environmental factors could have caused the more westernly crust (now basin and range) to melt. If this melt were pushed eastwards, it could accumulate below the Colorado plateau crust, creating more layers of buoyancy.

During this time, the Laramide slab was giving off water, which then migrated upwards into the lithosphere. Around the Colorado plateau, it is proposed that this water interacted with the mantle, leaching it of heavy elements. This excess water could have also weakened the lithosphere, allowing it to contract and become more tall during this period of compression. Combined, this would see a particularly tall crust layer supported by a light and more buoyant mantle layer.

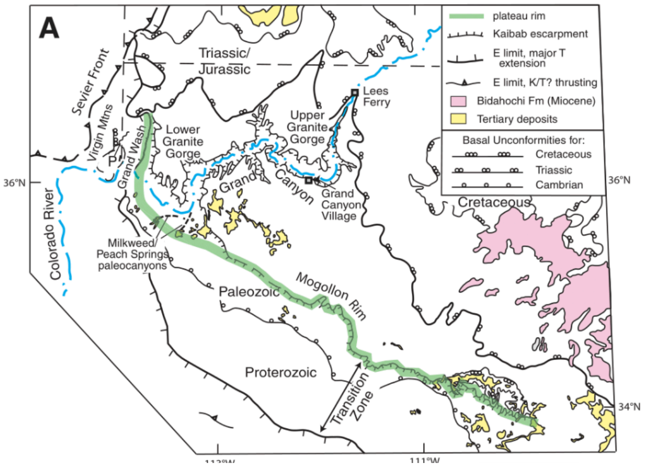
As the Laramide slab fell off around 40Ma, this transition could also have led to uplift. The mantle at the base of the lithosphere is very dense, and would have significantly weighed down the much more buoyant crust. When the subducting slab fell deeper into the mantle, it could have taken 120km out of the originally 200km thick lithosphere with it. As this heavy lower lithosphere fell off the crust, this space would have filled with hot asthenosphere material. This could explain a period of uplift around or after 40Ma, when the now low density lithosphere is pushed out of the mantle due to buoyancy.

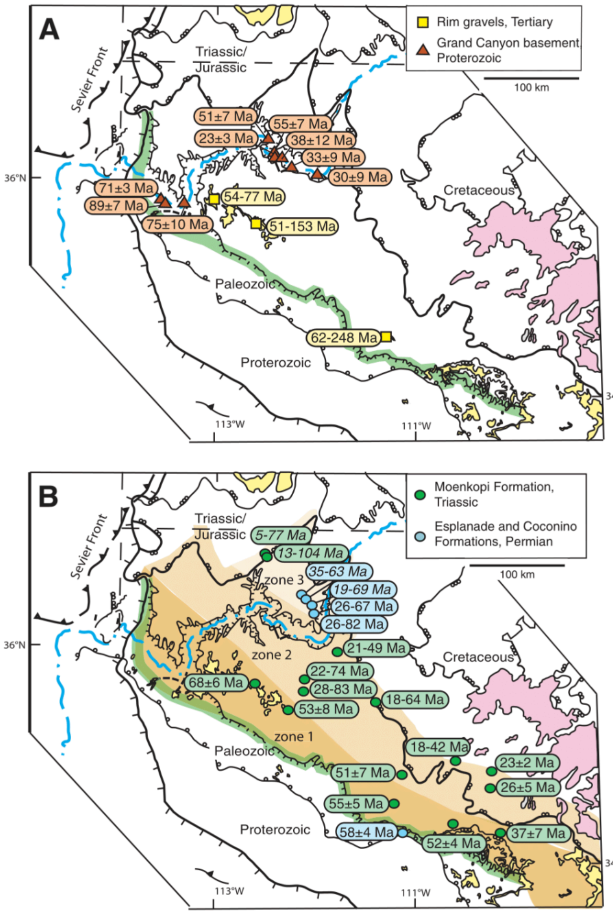
There are also theories about uplift within the last 5Ma. As the Colorado plateau has a similar thickness to the great plains to the east, it requires some explanation for the relative uplift. This may be due to mantle upwelling. A gravity free air anomaly map of North America shows a strong positive anomaly centered on Yellowstone, and extending into the colorado plateau. Under a uniform mantle, we should expect sections of the crust to rise and fall until reaching an equilibrium at zero anomaly. The existence of this anomaly implies that there may be some strong sub-crustal force.

One explanation of this is a large scale mantle upwelling due to convection. As hot material rises in the mantle, its buoyancy provides upwards force to elevate the colorado plateau. Evidence for this comes from seismic data on the 470km and 660km boundaries in the mantle. In hotter mantle rock, these phase transitions should occur at higher pressures, deeper in the earth. There is evidence for this below western North America.

Submarine sediments stopped being deposited as soon as the Colorado plateau became above sea level, so the fossil record can only set an earliest bound for the beginning of uplift. Using helium dating and argon-argon dating, it is possible to determine if and when apatite, zircon, or some specific other minerals were exposed to warm temperatures at the surface (~100 C). The He will propagate out of the mineral grains significantly faster at higher temperatures, so measuring the concentration towards the center vs the sides can give useful dating information.

For the samples which have been narrowly dated, this gives some river eroded gravel samples ages of 20-40Ma, and others 70-90Ma. This implies a large amount of erosion becoming increasingly deep during these periods, indicators of uplift. These can be further analyzed with the elevation at which these samples are found. This agrees with an initial period of uplift at the beginning of flat slab subduction, and then a second period when the slab began to fall off.


A
plateau rim
Kaibab escarpment
E limit, major T extension
E limit, K/T? thrusting
Bidahochi Fm (Miocene)
Tertiary deposits
Basal Unconformities for:
Cretaceous
Triassic
Cambrian
Sevier Front
Virgin Mtns
Grand Wash
Triassic/ Jurassic
Lees Ferry
Upper Granite Gorge
Lower Granite Gorge
Grand Canyon
Grand Canyon Village
Colorado River
Milkweed/ Peach Springs paleocanyons
Cretaceous
Mogollon Rim
Paleozoic
Proterozoic
Transition Zone
36°N
34°N
111°W


A
Rim gravels, Tertiary
Grand Canyon basement Proterozoic
100 km
Sevier Front
Triassic/ Jurassic
51±7 Ma
23±3 Ma
55±7 Ma
38±12 Ma
33±9 Ma
30±9 Ma
71±3 Ma
89±7 Ma
75±10 Ma
54-77 Ma
51-153 Ma
62-248 Ma
Cretaceous
Paleozoic
Proterozoic
36°N
34°N
113°W
111°W
B
Moenkopi Formation, Triassic
Esplanade and Coconino Formations, Permian
100 km
Sevier Front
Triassic/ Jurassic
5-77 Ma
13-104 Ma
35-63 Ma
19-69 Ma
26-67 Ma
26-82 Ma
21-49 Ma
zone 3
zone 2
zone 1
68±6 Ma
22-74 Ma
28-83 Ma
53±8 Ma
18-64 Ma
18-42 Ma
23±2 Ma
26±5 Ma
51±7 Ma
55±5 Ma
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Sources:
R.M. Flowers B.P. Wernicke K.A. Farley 2008
Unroofing, incision, and uplift history of the southwestern Colorado Plateau from apatite (U-Th)/He thermochronometry
Figures were from here

Nadine McQuarrie Clement G. Chase 1999
Raising the Colorado Plateau

Eugene Humphreys, Erin Hessler, et al.
How Laramide-Age Hydration of North American Lithosphere by the Farallon Slab Controlled Subsequent Activity in the Western United States

G. G. Roberts, N. J. White, G. L. Martin-Brandis, A. G. Crosby 2012
An uplift history of the Colorado Plateau and its surroundings from inverse modeling of longitudinal river profiles

Atmospheric Dynamics of Desert Thunderstorms and Rainbombs

Vinicius Nevoa

Introduction

Central Arizona's arid climate belies a dramatic summertime season marked by intense, short-lived thunderstorms. These storms frequently unleash "rainbombs," sudden, extreme downpours delivering very high rainfall rates over small areas. Understanding the atmospheric dynamics behind desert thunderstorms and rainbombs is critical both for advancing meteorological science and for public safety in a region prone to flash flooding. In what follows, we explore the thermodynamic and kinematic environment of the Sonoran Desert, the mechanisms that trigger convection, and the microphysical and dynamical processes that create rainbombs.

Developing Convective Potential and Lifting Mechanism

The thermodynamic environment of Central Arizona during the monsoon season is characterized by intense surface heating and mid-level dry air. By mid-afternoon, sun-baked desert soils commonly elevate near-surface temperatures into the range of 40–45 °C. Aloft, a persistent dry layer between roughly 500 and 700 hPa maintains a steep lapse rate, endowing the atmosphere with abundant convective available potential energy (CAPE)—often exceeding 1,000 J kg^{-1}. This substantial CAPE, combined with afternoon moisture surges from the Gulf of California and eastern Pacific, sets the stage for explosive convective development once any capping inversion is breached. Surface moisture itself is enhanced locally by irrigated agricultural fields and urban irrigation, raising dewpoints enough to feed developing updrafts. Yet a strong capping inversion frequently suppresses storms until late afternoon, when accumulated heating and moisture finally erode the lid.

Storm initiation in this environment typically requires a lifting mechanism, and in Central Arizona two forcings play the leading roles: orographic uplift and outflow-boundary convergence. Mountain breezes driven by afternoon heating push air upslope along the Mogollon Rim and ranges such as the Catalinas and Superstitions; parcels lifted in this manner can reach their level of free convection on the ridges. Simultaneously, the collision of valley breezes with prevailing southwesterlies can produce narrow corridors of convergence in the lower troposphere, seeding convective cells. Once isolated cells form, their downdrafts generate cold-pool outflows—density currents that spread laterally at speeds of 5–10 m s^{-1}. When these gust fronts encounter undisturbed air, they lift it, igniting successive generations of new cells in a classic multicell mode.

Microphysical Processes and Rainbombs

Within these vigorous convective cores, microphysical processes intensify precipitation rates. Strong updrafts exceeding 10 m s^{-1} suspend and grow graupel and hail particles, while the coalescence of water droplets accelerates. As precipitation falls into the exceptionally dry subcloud layer, sublimation and evaporation cool the descending air, accelerating the downdraft. These cold, rain-laden downdrafts concentrate intense rainfall into narrow shafts that strike the surface with astonishing severity: rainbombs. Defined as convective cores producing more than 100 mm h^{-1} over square-kilometer scales, rainbombs in Arizona can deliver 20–50 mm of rain in under ten minutes—enough to overwhelm dry washes and urban drainage in moments.

Kinematically, desert thunderstorms exhibit both robust updrafts and potent downdrafts. The intense updrafts support large hydrometeors and strong electrification, yielding frequent cloud-to-ground lightning and occasional small hail. The cold pools generated by evaporative cooling under heavy cores act as miniature density currents, spreading out at the surface to form gust fronts that locally lift air to form new cells. It is within these descending cold pools that rainbombs are embedded, their heavy precipitation cores tracking with the leading edges of the outflows.

Impacts and summary

The hazards posed by desert thunderstorms and rainbombs are many. Flash flooding ranks highest: dry arroyos that normally run bone-dry become raging torrents in minutes, while urban streets fill with life-threatening runoff. Dust storms, or haboobs, often accompany or follow the downdraft winds as they pick up loose sand and grit, reducing visibility to near zero. Lightning strikes and hail add further risk to anyone caught outdoors. In summary, the interplay of intense daytime heating, monsoonal moisture advection, orographic forcing, and vigorous microphysics produces the spectacular yet hazardous phenomena of desert thunderstorms and rainbombs in Central Arizona.

References

1. Houze, R. A., Jr. (1993). *Cloud Dynamics*. Academic Press.

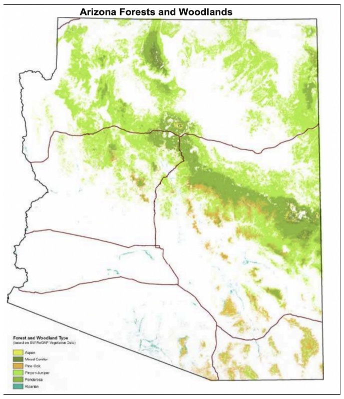
2. Jensen, E. J., & Braham, R. R., Jr. (2000). Microphysical aspects of high-reflectivity cores in desert convection. *Atmospheric Research*, 56(1–4), 3–16. https://doi.org/10.1016/S0169-8095(00)00040-8

3. Maddox, R. A. (1983). Areal distribution of mesoscale convective complexes. *Monthly Weather Review*, 111(3), 1358–1369. https://doi.org/10.1175/1520-0493(1983)111<1358:ADOMCC>2.0.CO;2

4. Fankhauser, J. C., & Reitan, C. H. (1973). Cold-pool structure and convective initiation. *Journal of the Atmospheric Sciences*, 30(2), 296–306. https://doi.org/10.1175/1520-0469(1973)030<0296:CPSACI>2.0.CO;2

Unique Trees of Arizona

Virginia Pistilli, Ge 136c



Arizona, home to diverse landscapes ranging from spruce and fir forests at high elevations and desert scrub, supports forests in approximately 27% of the state by area [1]. All 6 traditional forest types as shown in the map left (Aspen, Mixed Conifer, Pine-Oak, Pinyon-Juniper, Ponderosa, and Riparian) are represented in the state, comprising 37 native coniferous and hardwood trees total [2]. As of 2020, by far the most prevalent forest type was Pinyon-Juniper (13,420,572 acres), characterized by mid-elevations, arid climate, and junipers interspersed with grassland and shrubland that, at higher elevations, becomes denser with more pinyon pines. Additionally, many trees are uniquely adapted to survive outside of forests in the Sonoran desert. Essential to understanding these biomes is understanding how these trees adapt to generally dry conditions, higher elevations, and extreme heat waves. We will examine such drought-tolerance adaptations through examining and comparing 4 unique Arizona trees: the Palo Verde (*Parkinsonia florida*), the Alligator Juniper (*Juniperus deppeana*), the Arizona Cypress (*Hesperocyparis arizonica,* formerly *Cupressus arizonica*), and the Velvet Mesquite (*Prosopis velutina*).

Palo Verde (Blue Palo Verde: *Parkinsonia florida* and Foothill Palo Verde: *Parkinsonia microphylla)*

The two species of Palo Verde comprise Arizona's state tree, making it culturally as well as ecologically significant. One can distinguish between the two species by form (Blue Palo Verdes grow up to 30 ft tall and form a broader crown while Foothill Palo Verdes grow only up to 20 ft tall and have a more twisted, irregular shape) and color, with Blue Palo Verdes taking on a blue green while Foothill Palo Verdes tend to have a more yellow tint. Palo Verde trees are easily identifiable by their striking green bark, as pictured in a Blue Palo Verde tree to the left. This phenomenon is an example of woody plant stem photosynthesis, in which plant stems, bark, or woody tissues either contain chloroplasts and perform photosynthesis from external CO2 (stem net photosynthesis) or can re-assimilate internally respired CO2 (stem recycling photosynthesis) [3]. Because the gas exchange with atmospheric CO2 through opening stomata comes with the trade off of water loss, such stem net photosynthesis and recycling photosynthesis ultimately improves *Parkinsonia* hydraulic function. In fact, light limitation studies have revealed that CO2 fixed through green *Parkinsonia* bark contributes directly to *in situ* growth [4]. Thus, woody plant stem photosynthesis allows the Palo Verde to reduce water loss through transpiration and increase available energy, allowing them to thrive across Southwestern United States desert regions, including the Sonoran Desert. Additionally, these trees are deciduous, shedding their leaves not in response to seasonal changes, but in response to drought. When water is limited, they can rely almost exclusively on their bark for organic carbon. In the spring with adequate moisture and nutrient availability, they bloom small yellow flowers, attracting pollinators to propagate through their seeds. Due to such interactions with pollinators and the shade they produce in otherwise sparse desert regions, the Palo Verde is considered a "nurse plant" and keystone species, protecting smaller cacti and other native plants from harsh sun, trampling, etc. As leguminous trees, they host nitrogen-fixing bacteria in their root nodules, increasing the relative abundance of nitrogen fixers in soil nearby and ultimately increasing available nitrogen for nearby plants and microbiota [5].

Alligator Juniper (*Juniperus deppeana)*

Moving away from the desert and into our Pinyon-Juniper woodlands, the Alligator Juniper is unique for its distinctive, blocky bark resembling alligator skin (right). But that's not all - these evergreen conifers can grow up to 60 ft tall and can live up to 500-1000 years in their arid or semi-arid, higher elevation habitats [6]. To conserve water without having to shed leaves in times of drought, Alligator Junipers have evergreen pointed, scale-like leaves to reduce water loss through transpiration, as well as seed-bearing cones that allow them to reproduce without wasting precious water on flowers. The seeds inside these cones are also protected, such that despite low seed germination rates, they can remain dormant in soil until adequate moisture arrives [8]. Such reproductive resiliency as well as prioritization of water use efficiency extends the lifetime of these trees, with the oldest tree of Arizona being a Alligator Juniper roughly 2,000 years old and marking the Giant Alligator Juniper Trail in Prescott, AZ [7]. Beyond these adaptations allowing such old Alligator Juniper survivors, Alligator Junipers are also of cultural and medicinal significance. The Zuni and Hopi groups have not only used Alligator Junipers for chewing gum (pith) and food (berries, ash for cooking), but to relieve bruising, swelling, stomach pain, and pain in childbirth [9].

Arizona Cypress *(Hesperocyparis arizonica*)

Next, we discuss another evergreen commonly found alongside Alligator Junipers but taking on a different reproductive strategy to survive the Pinyon-Juniper woodland as well as other native rocky slopes and riparian biomes and up to elevations of 8,000 ft. These cypresses can grow up to 90 feet tall, forming dense crowns to promote shade and, like the Alligator Juniper, with scaly leaves to minimize water loss through evaporation. Within the first year of growth, Arizona Cypresses form a deep, well-defined taproot system with many lateral roots to promote stability on rocky slopes and to maximize water uptake [10]. While their seeds are contained in cones (48-112 seeds each), they are spread not through the dropping of cones and germination with adequate moisture (as is the case for the Alligator Juniper), but when fire, heat, desiccation, or other stress opens the cones while they are on the tree. Additionally, these seeds germinate ideally in bare mineral soil without a litter layer and are sensitive to moisture, making them especially fit to thrive in drier conditions following their release [11].

Velvet Mesquite (*Neltuma velutina)*

Similarly to the Palo Verde, the Velvet Mesquite is leguminous, acting as a nurse tree for other species and increasing bioavailable ecosystem nitrogen. Also similar to the Palo Verde, it is a woody stem photosynthesizer through its young green branches. What makes the Velvet Mesquite unique is in its ability to form dormant buds along its underground stem [12]. When aboveground plant is trampled, burned, cut, or stressed from extreme drought, these buds are able to vegetatively regenerate the plant, making it an extremely resilient character in the Sonoran desert [12]. It is this resilience that has contributed to its success across the southwest, such that it is considered invasive in some deserts outside of its native Sonoran range. Whereas the increase in agriculture and fire harm most species, these stressors end up promoting this vegetative propagation and the spread of the Velvet Mesquite [13].

References:

1. Arizona Department of Forestry and Fire Management. (2020, October 1). *Arizona Forest Action Plan: A collaborative analysis of natural resource conditions, trends, threats, and opportunities*.
2. Arizona Department of Forestry and Fire Management. (2022). *2022 Arizona forest health highlights*. https://www.fs.usda.gov/foresthealth/docs/fhh/AZ_FHH_2022.pdf \
3. Berry, Z. C., Ávila-Lovera, E., De Guzman, M. E., O'Keefe, K., & Emery, N. C. (2021). Beneath the bark: Assessing woody stem water and carbon fluxes and its prevalence across climates and the woody plant phylogeny. *Frontiers in Forests and Global Change, 4*, Article 675299. https://doi.org/10.3389/ffgc.2021.675299
4. 4. Ávila-Lovera, E., Haro, R., Choudhary, M., Acosta-Rangel, A., Pratt, R. B., & Santiago, L. S. (2024). The benefits of woody plant stem photosynthesis extend to hydraulic function and drought survival in *Parkinsonia florida*. *Tree Physiology, 44*(3), tpae013. https://doi.org/10.1093/treephys/tpae013
5. Gamiz, G. I. (2024). *Buffelgrass effects above and belowground in the Sonoran Desert* (Publication No. 31295471) [Master's thesis, The University of Arizona]. *ProQuest Dissertations & Theses Global*.
6. UC Davis Arboretum and Public Garden. *Alligator juniper | Juniperus deppeana*. UC Davis. https://arboretum.ucdavis.edu/tree-database/alligator-juniper-juniperus-deppeana
7. Lawrence, K. *There's no other historical landmark in Arizona quite like this 2,000-year-old tree*. OnlyInYourState. https://www.onlyinyourstate.com/experiences/arizona/oldest-tree-az
8. Tirmenstein, D. A. (1999). *Juniperus deppeana*. In U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, *Fire Effects Information System*. https://www.fs.usda.gov/database/feis/plants/tree/jundep/all.html
9. Curtin, L. S. M. (1997). *Healing herbs of the Upper Rio Grande: Traditional medicine of the Southwest Chicano heritage* (M. Moore, Ed., illustrated, revised ed.). Western Edge Press.
10. Johnson, L. C. (1974). *Cupressus* L. cypress. In C. S. Schopmeyer (Ed.), *Seeds of woody plants in the United States* (Agric. Handb. 450, pp. 363–369). U.S. Department of Agriculture, Forest Service.
11. Sullivan, J. (1993). *Hesperocyparis arizonica*. In U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer), *Fire Effects Information System*. https://www.fs.usda.gov/database/feis/plants/tree/hesari/all.html
12. Uchytil, R. J. (1990). *Prosopis velutina*. In U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer), *Fire Effects Information System*. https://www.fs.usda.gov/database/feis/plants/tree/popvel/all.html
13. Turner, R. M. (1963). Growth in four species of Sonoran Desert trees. *Ecology, 44*(4), 760–765. https://doi.org/10.2307/1933023

Vanadinite and Wulfenite

Paolo Sanchez | Ge 136c | Spring 2025

In the realm of mineralogy, Arizona is well-established as one of the world's foremost areas to find rare and beautiful ore minerals. The unique geology of Arizona has made it an historic source of copper, gold, silver and uranium, as well as the site of 112 new mineral discoveries [1].

Although not as well-known as ores of copper (azurite and malachite), or silver and gold, the minerals vanadinite (Figure 1a) and wulfenite (Figure 1b) are prominent as secondary ore minerals, formed from the alteration of primary ore minerals—generally sulfides such as galena (PbS) and molybdenite (MoS_2) [2,5]. These minerals are commonly associated with other secondary ore minerals from lead-rich deposits such as cerussite ($PbCO_3$), barite ($BaSO_4$), mimetite ($Pb_5(AsO_4)_3Cl$), and calcite ($CaCO_3$) [2]. In some rare cases, both these minerals can also occur together. Although these two minerals only constitute a minor part in Arizona's mineralogical diversity and extensive mining history, their occurrence in the state has made Arizona a world-class locality for mineralogists and mineral enthusiasts alike.

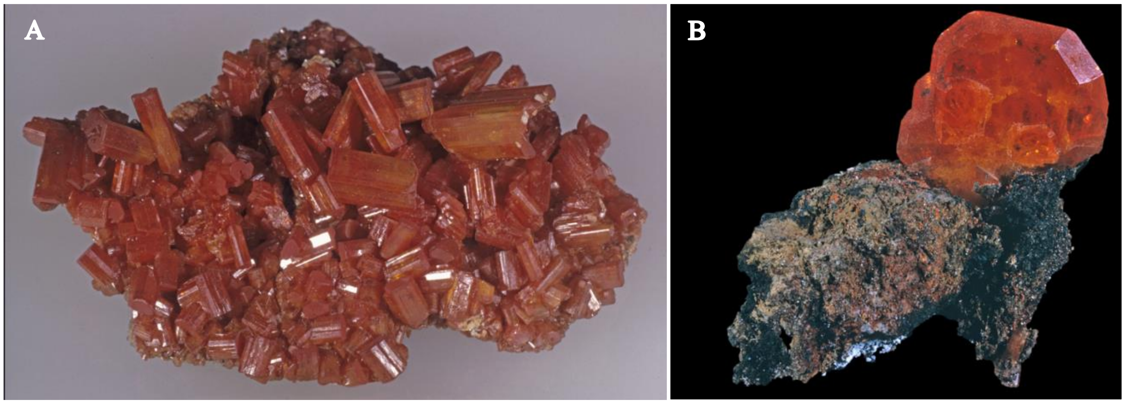


Figure 1: a) Vanadinite from the Old Yuma Mine, Pima Co., AZ. b) Wulfenite from the Red Cloud Mine, La Paz Co., AZ.

Vanadinite [$Pb_5(VO_4)_3Cl$]: One of the main ore minerals for vanadium, it forms distinctly hexagonal crystals and is often associated as a minor byproduct of gold and silver mining. In the early 1800s, vanadium was discovered as a new chemical element from this mineral in hydrothermal deposits from Chihuahua, Mexico [5]. Before the 2000s, Arizona has been the primary source of quality vanadinite crystals for museums and collectors. Today, most vanadinite in rock and mineral shows come from the Midelt Province of Morocco.

Wulfenite [$PbMoO_4$]: A minor ore of molybdenum, it has been nicknamed "yellow lead spar" due to its orange to yellowish color. It is known to grow in a myriad of morphologies, from triangular pyramids to thin tabular crystals. Wulfenite was originally discovered in Carinthia, Austria and named after Austrian mineralogist, Franz von Wulfen. The underlying tetragonal crystal structure of wulfenite was first characterized in 1919 by Roscoe Dickinson, the PhD advisor to Linus Pauling at Caltech [3]. In some unique geologic environments, it may precipitate directly from volcanic fumarole gas, in temperatures 400 - 500 ºC [9].

Color:

The deep red to orange color of both vanadinite and wulfenite has contributed to their aesthetic value to mineral collectors, and rarely, as gemstones. When examining UV-Vis absorption spectra of both minerals (Figure 2), there are distinct absorption bands centering in the UV wavelengths (~200-250 nm). This is due to a phenomenon that is relatively rare in the mineral world. Most minerals generally get their color from one of three processes: 1) constituent metal ions, where electrons jump between d-band energy levels, usually resulting in weak absorbance; 2) intervalence charge transfer (IVCT), involving electrons jumping between mixed oxidation states between metal ions (e.g., Fe^{2+} and $Ti4^{+}$); or 3) ionizing radiation, which can change the oxidation state of ions and create 'color centers' which can absorb strongly in visible wavelengths [4].

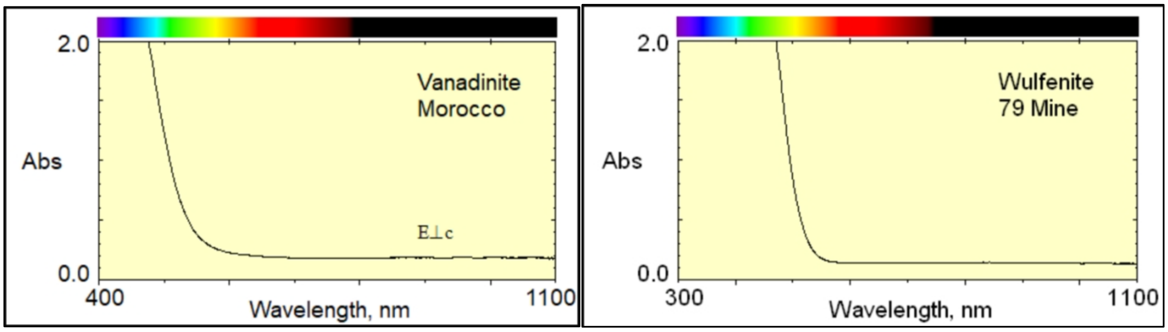
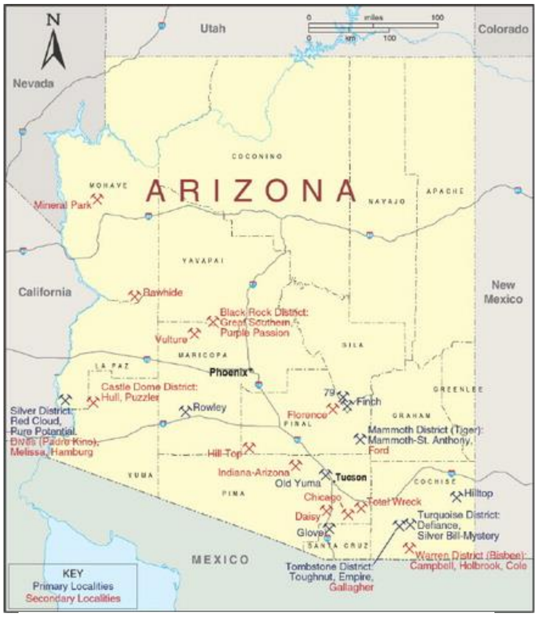


Figure 2: Optical absorption bands of vanadinite (left) and wulfenite (right), showing very strong absorption centered around UV wavelengths [4]

In wulfenite and vanadinite, however, color comes from trace amounts of chromate anions (CrO_4^{2-}) replacing either molybdate (MoO_4^{2-}) in wulfenite or vanadate (VO_4^{3-}) in vanadinite. Chromium as the Cr^{3+} ion is known to produce either red or green colors, like in rubies and emeralds, respectively. In contrast, Cr^{6+} in chromate anions strongly pull electrons from the surrounding oxygen ligands, resulting in ligand-to-metal charge transfer (LMCT), which strongly absorbs photons in the ultraviolet wavelengths (Figure 2) [6]. The tail end of these absorption bands is within the blue and green wavelengths, resulting in vivid yellow, orange and red colors from only ~100 ppm concentrations of chromium.

Arizona localities: Vanadinite and wulfenite have been mined in Arizona both for ore and for the mineral collector market for the past hundred years, with mines such as the Total Wreck Mine (yes, it's literally called that) in Pima County producing wulfenite crystals as a byproduct since the 1880s and the Apache Mine in Gila County producing vanadinite since the 1920s [2]. Wulfenite specimens from Arizona have been touted as the world's finest, featured in several world's fairs in the 20th century and resulting in wulfenite officially becoming Arizona's state mineral in 2017 [8]. Today, most of these mines have either been shut down and/or are now closed off to collecting, yet a few notable producers of these minerals, such as the Red Cloud Mine in Yuma, offer tourists a chance to find for wulfenite crystals in the dumps for a fee [7]. Other mines have become abandoned, yet some minerals can still be found in dump material.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Black Rock District:
Great Southern,
Purple Passion
Vulture
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GILA
LA PAZ
Phoenix
Castle Dome District:
Hull, Puzzler
GREENLEE
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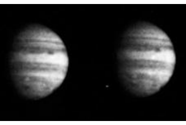
Finch
Silver District:
Red Cloud,
Pure Potential,
Bivins (Padre Kino),
Melissa, Hamburg
Rowley
Florence
PINAL
GRAHAM
Mammoth District (Tiger):
Mammoth-St. Anthony,
Ford
Hill-Top
YUMA
Indiana-Arizona
Old Yuma
Tucson
PIMA
COCHISE
Hilltop
Chicago
Total Wreck
Daisy
Turquoise District:
Defiance,
Silver Bill-Mystery
Glove
SANTA CRUZ
MEXICO
Warren District (Bisbee):
Campbell, Holbrook, Cole
Tombstone District:
Toughnut, Empire,
Gallagher
KEY
Primary Localities
Secondary Localities

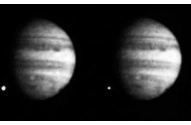
Figure 3: Wulfenite localities in Arizona. From [2].

References:

[1] "Arizona Localities" n.d. mindat.com. [2] Baldh, K. 2018. *Rocks & Minerals*. **94**. [3] Dickinson, R.G. 1919. *J. of the Am. Chem. Soc.* **42** (1). [4] Rossman, G.R. n.d. "The Colors of Minerals" minerals.gps.caltech.edu. [5] Perez-Bustamente de Monasterio., J.A. 1990. *F. J. of An. Chem*. **337** (2). [6] Talla, D. et al. 2013. *Phys. Chem. Minerals* **40**. [7] "Trip Planner". n.d. redcloudmine.com. [8] "State Mineral 41-860.04". *Arizona Revised Statutes*, 2017. [9] "Vanadinite" n.d. mindat.com.



The Remarkable Life and Legacy of Eugene “Gene” Shoemaker



Elin Stenmark

Eugene “Gene” Merle Shoemaker (BS ’47, MS ’48, MS ’54, PhD ’60), son of teachers Muriel May and George Estel, was born on April 28, 1928, in Los Angeles, CA. [1] His childhood was split between California, Oregon, New York, and Wyoming as his parents moved for work and education. [2, pp. 1-4] After years of rock collecting and attending science programs at the Buffalo Museum of Science, as well as taking classes at Fairfax High School and LA High in Los Angeles, he graduated in two years and enrolled at Caltech at the age of 16, with his sight set on geology. [2, pp. 4-5]

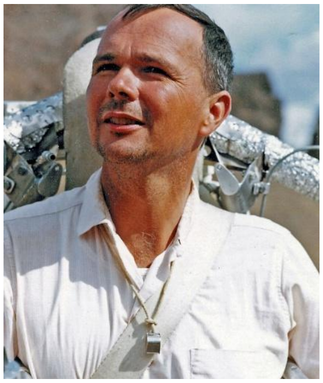


Fig. 1: Shoemaker carrying a “rocket belt” jetpack prototype at Hopi Buttes, AZ, 1966. Image credit: USGS

Early Career In light of WW2, only two faculty members, John Peter Buwalda and Chester Stock, were teaching in the geology department. [2, p.6] In his senior year, faculty returned, and Shoemaker overloaded on geology courses and wrote a senior thesis on the Pacoima Area to earn a bachelor’s degree in Geology. [2, p.7; 7] Following the advice of the Caltech-fostered assistant professor and Shoemaker’s self-proclaimed hero, Richard “Dick” Jahns, he stayed at Caltech to study pre-Cambrian rocks in New Mexico for his master’s degree, before turning to the USGS and an assignment at the Colorado Plateau in Grand Junction, CO, which he described as having “died and gone to heaven geologically”. [2, pp.8-9; 8] With a goal of being “the last of a dying generation of general geologists”, he pursued a doctorate at Princeton, studying petrology and geochemistry in the field before committing to a thesis on Meteor Crater. [2, pp.10-14; 6]

Father of Astrogeology In a Caltech oral history interview, Shoemaker said that he “couldn’t imagine anything more exciting that [he] could possibly do than to get to the moon”. [2, p.15] In 1956, he had proposed making lunar maps to the director of the USGS, and 5 years later, he became the founder and director of the USGS Astrogeology Branch, as well as director of the 1965 USGS Astrogeology Science Center in Flagstaff, AZ, whose current mission statement is “to help humanity understand our solar system by maximizing the scientific and technological return from planetary missions through scientific research, software development, and the creation of spatial data products and standards.” [1; 3; 4] To the detriment of his personal ambitions, amid gathering support for his program, Shoemaker was diagnosed with Addison’s disease, an adrenal gland disorder, which disqualified him from serving as astronaut. [1; 2] Instead, he trained astronauts in Meteor Crater and served as the principal investigator for the Apollo 11 surface missions. [5] In a 2000 interview, Leon Silver, the W. M. Keck Foundation Professor for Resource Geology, Emeritus, and one of Shoemaker’s contemporaries on the Apollo missions, relayed a little-known but integral role Shoemaker played in this mission. After encountering unexpectedly rough terrain at the proposed landing site, Neil Armstrong had to manually land the spacecraft on the lunar surface. The control room subsequently lost track of the spacecraft’s position, prompting a multi-hour-long hunt that culminated in Shoemaker finding them so that they could safely return to Earth. [5]

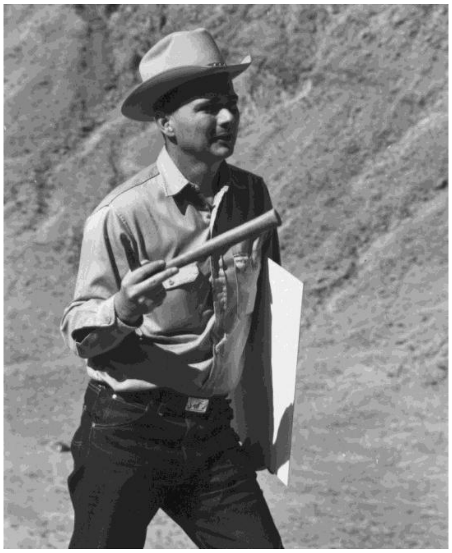


Fig. 2: Shoemaker at Meteor Crater, AZ. Image credit: USGS

“**My real forte was field geology – that’s what I loved.**” – E. M. Shoemaker [2, p.8]

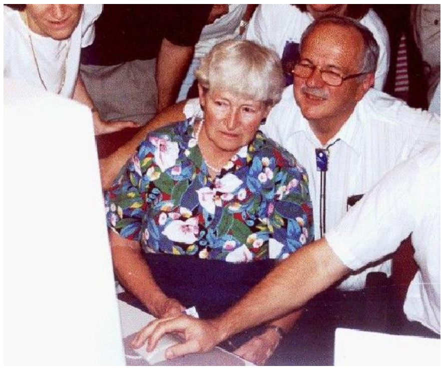
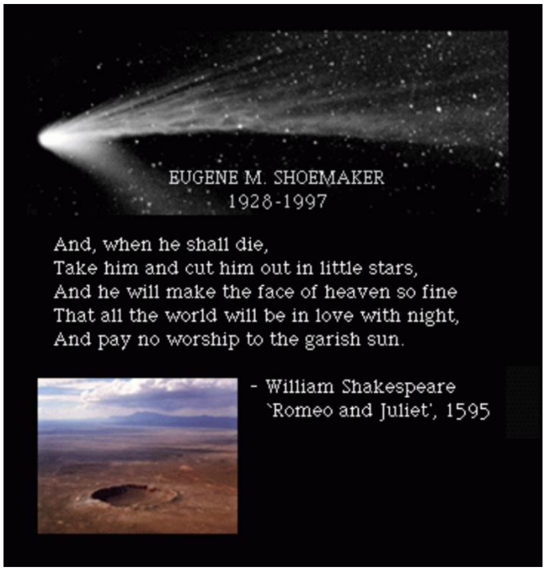


Fig. 3: The Shoemakers watching Shoemaker-Levy 9 impact Jupiter at the Space Telescope Science Institute, Baltimore, MD. Image credit: John Aiello/STScI

Caltech & Comets Shoemaker described Caltech as having "this old silver thread that tugs you back". [2, p.19] After a few years of part-time commitment, he returned to Caltech full-time between 1969-1985, serving as the GPS Division Chair in his first three years. [9] He collaborated with Eleanor F. "Glo" Helin under the Palomar Planet-Crossing Asteroid Survey (PCAS) to search for Apollo asteroids and other impactors with their 46-cm Schmidt telescope, as well as with his wife Carolyn Shoemaker on the Palomar Asteroid and Comet Survey (PACS). [11] The latter pair have been accredited with the discovery of 32 comets and 1125 asteroids, the most famous of them Shoemaker-Levy 9, co-discovered with David Levy in 1993. [9; 12] This comet fragmented before impact on Jupiter in 1994, marking the first observation of a collision between Solar System objects. [13]

One Final Journey On July 18, 1997, on a quest to find and characterize impact craters in Australia, Shoemaker passed away in a head-on collision near Alice Springs that, at the time, left his wife severely injured. Susan Kieffer writes that Shoemaker possessed a "warm, twinkling humanness, [...] unfailingly generous spirit, [...] intellectual honesty, [...] romance and love in his eyes for Carolyn, and [...] unflagging enthusiasm for life and its unfolding." [1] As the only person to have had a vial of his ashes scattered on another solar system body, Shoemaker made the moon his final resting place when the Lunar Prospector spacecraft impacted on a south pole crater on July 31st, 1999. [14] The crater was later renamed 'Shoemaker' in his honor. On the vial, a picture of comet Hale-Bopp, the last comet he and Carolyn observed, and Meteor Crater are accompanied by the following *Romeo and Juliet* quote: "And, when he shall die / Take him and cut him out in little stars / And he will make the face of heaven so fine / That all the world will be in love with night / And pay no worship to the garish sun." [14; 10]



EUGENE M. SHOEMAKER
1928-1997

And, when he shall die,
Take him and cut him out in little stars,
And he will make the face of heaven so fine
That all the world will be in love with night,
And pay no worship to the garish sun.

- William Shakespeare
'Romeo and Juliet', 1595

Fig. 4: Shoemaker's commemorative plaque carried aboard the Lunar Prospector mission. [14]

References:

[1] Kieffer, Susan W. "Eugene M. Shoemaker (1928-1997)." *National Academy of Sciences*, 2015, https://www.nasonline.org/wp-content/uploads/2024/06/shoemaker-eugene.pdf

[2]: Eugene Merle Shoemaker Oral History Interview, 1995-10-26 - 1995-10-26. Caltech Oral History Interviews, OH. California Institute of Technology Archives and Special Collections.

[3]: Chapman, Mary G. *Gene Shoemaker - Founder of Astrogeology*. U.S. Geological Survey. https://www.usgs.gov/centers/astrogeology-science-center/gene-shoemaker-founder-astrogeology Retrieved May 24, 2025.

[4]: U.S. Geological Survey. Astrogeology Science Center – About. https://www.usgs.gov/centers/astrogeology-science-center/about#:~:text=Mission%20Statement%3A%20To%20help%20humanity,spatial%20data%20products%20and%20standards. Retrieved May 24, 2025

[5]: Silver, Leon T. Interview by Shirley K. Cohen. Pasadena, California, December 12 and 20, 1994, January 9, 16, and 25, 1995, and February 23, 2000. Oral History Project, California Institute of Technology Archives. Retrieved May 22, 2025 from the World Wide Web: http://resolver.caltech.edu/CaltechOH:OH_Silver_L

[6]: Shoemaker, Eugene M. *Impact Mechanics at Meteor Crater, Arizona*. Princeton University, 1960.

[7]: Shoemaker, Eugene Merle and Glover, Patrick Norman and Muehlberger, William R. and Nicolai, Fred H. (1947) *A Geologic Report on the Pacoima Area.* Senior thesis (Major), California Institute of Technology. doi:10.7907/NG1S-EQ56. https://resolver.caltech.edu/CaltechTHESIS:07072015-115042010

[8]: Shoemaker, Eugene Merle. *Preliminary Geologic Map of Part of the Sinbad Valley-Fischer Valley Anticline, Colorado and Utah; Structure Map and Sections of the Sinbad Valley-Fischer Valley Anticline, Colorado and Utah*. U.S. Geological Survey, 1952, https://doi.org/10.3133/ofr52138

[9]: Division of Geological and Planetary Sciences. Caltech. *Eugene Shoemaker.* https://www.gps.caltech.edu/people/eugene-shoemaker Retrieved May 24, 2025

[10]: The Planetary Society. *Eugene Shoemaker.* https://www.planetary.org/profiles/eugene-shoemaker Retrieved May 24, 2025.

[11]: Helin, E. F., and E. M. Shoemaker. "The Palomar Planet-Crossing Asteroid Survey, 1973–1978." *Icarus*, vol. 40, no. 3, 1979, pp. 321-328. https://doi.org/10.1016/0019-1035(79)90021-6

[12]: Shoemaker, E. M., Shoemaker, C. S., and Levy, D. H. "Collision of P/Shoemaker-Levy 9 with Jupiter." *AAS/Division for Planetary Sciences Meeting Abstracts*, vol. 25, June 1993, p. 06.10. https://ui.adsabs.harvard.edu/abs/1993DPS....25.0610S

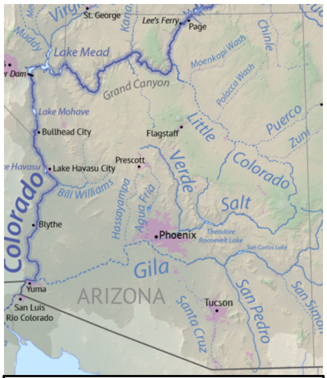
[13]: National Aeronautics and Space Agency. *Comet Shoemaker-Levy 9.* https://science.nasa.gov/solar-system/comets/p-shoemaker-levy-9/ Retrieved May 24, 2025

[14]: Porco, Carolyn C. *Eugene M. Shoemaker – A Tribute*. 2022. https://ciclops.org/public/tribute.html Retrieved May 24, 2025.

Report Banner Image: Impact of Shoemaker-Levy 9 Fragment W and Jupiter as seen by Galileo on July 22, 1994. Image credit: NASA/JPL-Caltech/Galileo Imaging Team

Dams in Arizona - kinds, shapes, sizes, how they generate power, and more

Ge136c – Central Arizona – May 30th - June 2nd – ST25 – Victor Vescu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Theodore Roosevelt Lake
San Carlos Lake
Gila
Yuma
San Luis Rio Colorado
ARIZONA
Santa Cruz
Tucson
San Pedro

Figure 1: AZ river network. USGS

According to the National Inventory of Dams, 372 of the 92,429 dams in the US are in Arizona. This puts the state last after Delaware (83), Alaska (111), Hawaii (126), and Rhode Island (235). Despite being one of the states with the fewest dams, Arizona stands out by having some of the most impressive and important dams in the country. The average dam age in Arizona is 70 years, slightly above the national average of 64 years. Dams can be categorized by shape and purpose. Each dam can be a combination of multiple types in the same category. There are 27 major dams in Arizona. A major dam is defined as either (a) a dam at least 15 meters tall with a storage capacity of 6.2 Mm^3 or (b) a dam of any height with a capacity of at least 31 Mm^3. The two largest reservoirs in the United States are both in Arizona: Lake Mead (behind Hoover Dam – 35.7 km^3), on the border between Arizona and Nevada, and Lake Powell (behind Glen Canyon Dam – 32.3 km^3), shared between Arizona and Utah. Some notable dam types found in Arizona, classified by shape, are:

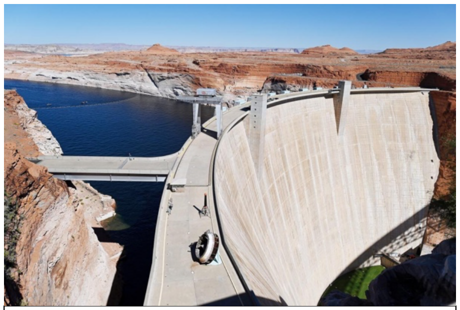


Figure 2: Glen-Canyon Dam: an arch-gravity dam used for hydroelectric power, irrigation, and recreation. Created Lake Powell on the Colorado. Source: Joshua Lott / Wash. Post

1. Arch Dam – a dam curved upstream to transmit the major part of the water load to the abutments. These can be double curvature arch dams if they are curved vertically as well as horizontally. Arch dams are supported by the walls of the canyon in which they are built. Examples are in Figures 2 and 3.
2. Buttress Dam – made of a watertight part supported at intervals on the downstream side by a series of buttresses. Spaced at regular intervals, the buttresses are built to divert the force that the water exerts onto the dam down to the dam's foundation. Examples are in Figures 4 and 5.
3. Embankment Dam - constructed from excavated natural materials or from industrial waste materials. If more than 50 percent of the total volume is formed of compacted earth material, they are also called Earth Dams. This is the most common type in the US.

4. Gravity Dam - a dam constructed of concrete and/or masonry, which relies on its weight and internal strength for stability. Due to their Δ cross-section, these have a large base and can only be built on a rock foundation.

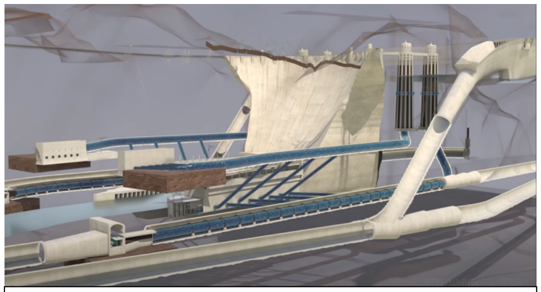


Figure 3: X-Ray view of the insides of the Hoover Dam. Hoover Dam is also an arch-gravity dam on the Colorado. Source: Animagraffs YouTube channel

Dam heights in Arizona:

- Greater Than 100 Ft: **39**
- 50-100 Ft: **57**
- 25-49 Ft: **158**
- Less Than 25 Ft: **118**

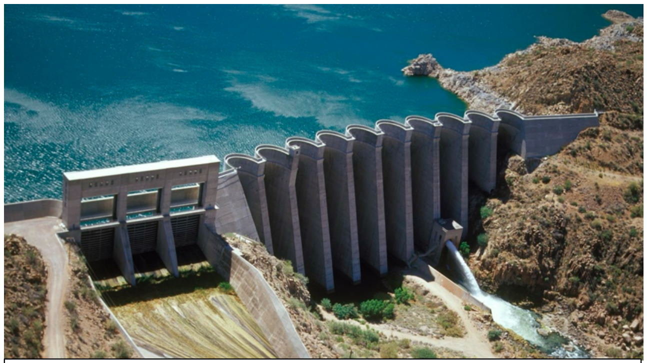


Figure 5: Bartlett Dam – a unique multiple-arch buttress dam on the Verde River. Primarily for irrigation and flood risk reduction. Source: Bureau of Reclamation

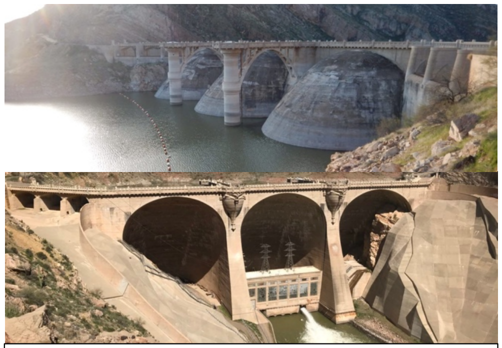


Figure 4: Front and back views of Coolidge Dam – a multiple-dome and buttress dam on the Gila River. Source: RJH Consultants

How power is generated:

Each generator has a several-foot diameter butterfly valve. The generator itself is a multi-story installation. Incoming water flows through a steel spiral case, or scroll case, that gradually narrows, such that water speeds up to pass through. At the center of this spiral case, there is a turbine wheel, called a runner, with fins that are driven by the fast-flowing water. The horizontal flow is guided vertically out by the runner and then out through a draft tube.

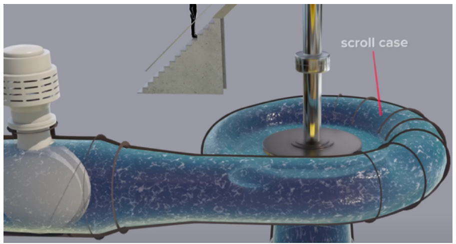


Figure 6: Diagram of how water flows to spin a turbine in a hydroelectric generator, such as those found at Hoover Dam. Person for scale. Source: Animagraffs YouTube channel

References:

[1] Collier, M., Webb, R. H., & Schmidt, J. C. (1996). *Dams and rivers: a primer on the downstream effects of dams* (Vol. 1126). US Department of the Interior, US Geological Survey.

[2] Norman, L. M., & Niraula, R. (2016). Model analysis of check dam impacts on long-term sediment and water budgets in Southeast Arizona, USA. *Ecohydrology & Hydrobiology*, *16*(3), 125-137.

[3] Stevens, L. E., Ayers, T. J., Bennett, J. B., Christensen, K., Kearsley, M. J., Meretsky, V. J., ... & Wegner, D. L. (2001). Planned flooding and Colorado River riparian trade-offs downstream from Glen Canyon Dam, Arizona. *Ecological Applications*, *11*(3), 701-710

Lowell Observatory and the Discovery of Pluto

Becky Williams Ge 136C Spring 2025

Figure 1: Pluto, imaged by New Horizons (credit: NASA)

The Founding of Lowell Observatory

Lowell Observatory, located in Flagstaff, Arizona, was established on May 28, 1894 by Percival Lowell. Lowell was not an astronomer by training, but he was interested in studying Mars and other planets. He commissioned the Clark telescope, a 24-inch refractive telescope, which was one of the largest telescopes at that time (Figure 2, left). He spent decades making detailed observations of Mars, and reached several conclusions, including some that we now know to be true: that Mars has an atmosphere, and lacks large permanent bodies of water. He also reached several conclusions that we now know are false: that the change in Mars's dark surface features is due to vegetation, and, most famously, that Mars harbors an extensive network of canals that must have been created by intelligent life [3]. It is unclear exactly why Lowell was so convinced that canals exist on Mars, but one likely possibility is that he was actually seeing a projection of the blood vessels in his eye and he interpreted the pattern as canals. In 1903, the observatory began using a camera to take photographs of observations (before, all observations had to be sketched by hand). Around that time, a spectrograph was also added to the observatory's toolbox, and in 1908 a spectrum of Mars showed absorption from water vapor and oxygen, a result that was disputed at the time, but proven true with subsequent observations [3].

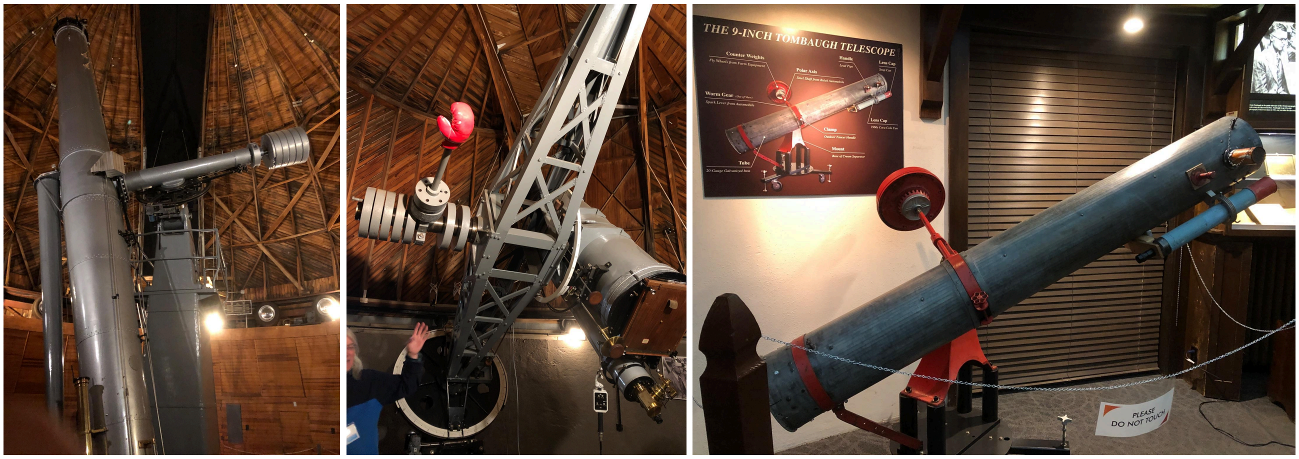


Figure 2: Telescopes at Lowell include the 24-inch Clark telescope (left), Pluto Discovery Telescope (center), and Clyde Tombaugh's homemade telescope (right) featuring a soup can as lens cap, faucet handle as clamp, and farm equipment as counterweights.

Discovery of Pluto

Lowell Observatory is perhaps best known for the discovery of Pluto [4]. In the late 19th century, astronomers noted that the orbits of Uranus and Neptune were consistent with the existence of a large body farther away from the Sun. This prompted Lowell in 1906 to begin a search for this mysterious planet, which was carried out unsuccessfully until Lowell passed away in 1916. Just over a decade later, in 1929, 23-year-old Clyde Tombaugh was hired to continue the search. Tombaugh was living on a farm in Kansas and had no formal education in the field of astronomy, but he was an excellent amateur astronomer, having built several telescopes himself, making use of assorted scraps around the farm (see Figure 2, right).

How do you find a planet? Tombaugh's job was to systematically take images of the night sky, using a 13-inch reflector telescope called an astrograph (see Figure 2, center), in regions where orbital calculations predicted the planet to be. In 1930, this meant using photographic plates, which were large glass plates placed in the back of the telescope, where the light was being focused to (and where you would put an eyepiece if you wanted to look through the telescope yourself). These glass plates, exposed to light from the stars, would

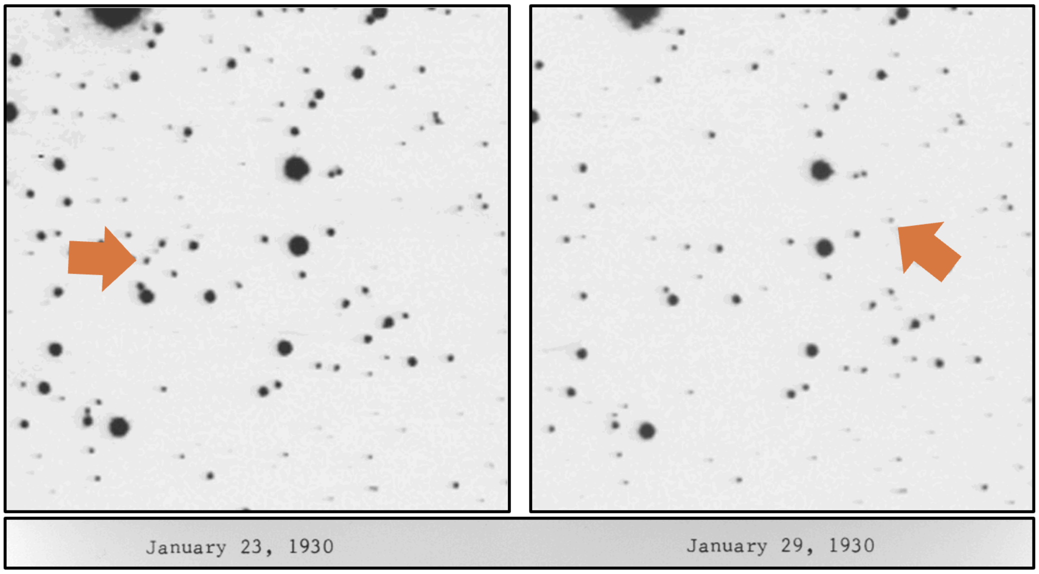


Figure 3: Pluto Discovery Plates (credit: Lowell Observatory Archives)

produce an image of the star field that the telescope was pointed at. By taking images of the same patch of sky over multiple nights, Tombaugh could look for points of light that were moving with respect to the rest of the star field. He used a device called a “blink comparator”, which allows the user to put two photographic plates side by side, and then flip quickly between the two. Using this method, any spots that are moving will jump out to the viewer. Within a year of commencing his search for the ninth planet, Tombaugh discovered a new planet on February 18th, 1930 [Figure 3]. This new planet needed a name, and the winning name came from a young girl from England, via a telegraph that stated “NAMING NEW PLANET PLEASE CONSIDER PLUTO, SUGGESTED BY SMALL GIRL, VENETIA BURNEY, FOR DARK GLOOMY PLANET” [4].

Other notable contributions:

In the early 1900s, there was an ongoing debate as to whether nebulae are in our galaxy, or are in fact their own galaxies outside of our galaxy (in short, astronomers could not agree on the size of the Universe). Vesto Slipher, working at Lowell Observatory, was the first to observe high redshifts of nebulae, writing that observations “showed these objects to be flying through space with most extraordinary speeds” [3]. Shortly after, Edwin Hubble at Mt. Wilson Observatory concluded that many of the objects called “nebulae” were at such large distances that they could not be located in our own galaxy. He proved this theory by observing Cepheid variable stars, which are stars that change brightness over short timescales, with an intrinsic luminosity that is strongly correlated with pulsation period [2]. Having established that the Universe is large and consists of many galaxies, Edwin Hubble then used Slipher’s observations, in conjunction with observations that Hubble made at Mt. Wilson Observatory, to conclude that the Universe is expanding [1].

Lowell Observatory continues to be a hub for space science, operating a 4.3-meter telescope about 40 miles outside of Flagstaff called the Lowell Discovery Telescope. Astronomers at Lowell today study a wide variety of topics, from asteroids to comets to stars. The original telescopes are no longer used for research, but are used nearly every night in public outreach events. Flagstaff is a dark sky city and continues to offer excellent views of the night sky.

Sources:

[1] Hubble, E. (1929). A relation between distance and radial velocity among extra-galactic nebulae. Proceedings of the National Academy of Sciences, 15(3), 168–173. https://doi.org/10.1073/pnas.15.3.168
[2] Leavitt, Henrietta S. (1908). "1777 variables in the Magellanic Clouds". Annals of Harvard College Observatory. 60: 87. https://articles.adsabs.harvard.edu/full/1907AnHar..60...87L
[3] Slipher, V. M. (1927). THE LOWELL OBSERVATORY. Publications of the Astronomical Society of the Pacific, 39(229), 143–154. http://www.jstor.org/stable/40692674
[4] The Home of Pluto: Lowell Observatory in Flagstaff, AZ. Lowell Observatory. (2025, May 1). https://lowell.edu/

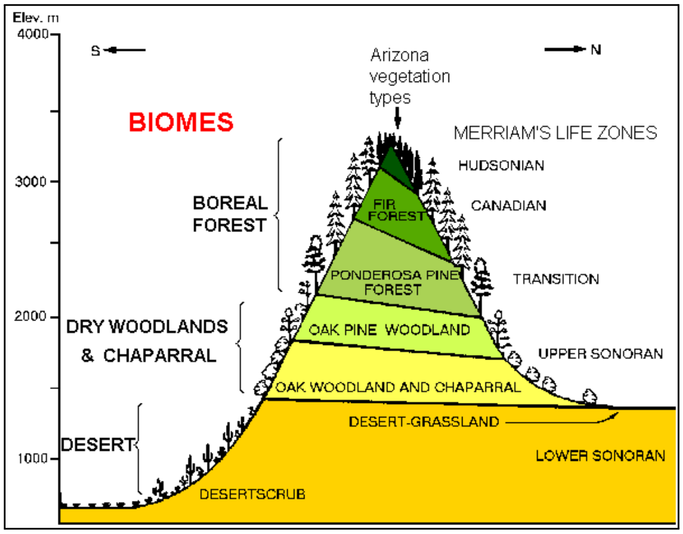
Biomes of Arizona

Ge 136C Jiahui Xie

Introduction

Known as the inland state with the most biological and ecological diversity, Arizona is home to an incredible number of different biomes and ecosystems that vary based on elevation, temperature, and other factors. From desert basins to forests, these distinct biomes also come with interesting animal and plant life. Now, the goal of this field guide would be to 1. describe the major biomes found across Arizona, especially those in central Arizona, 2. explain the climatic and geographic factors that created these unique habitats 3. take a closer look at the Sonoran desert as it is the main biome of Central Arizona and 4. how current environmental factors, being climate change are changing these landscapes in real time.

There are six major biomes in Arizona, largely due to its dramatic elevation differences in Arizona topography, as explained by the Merriam effect, which describes how plants and communities of living organisms (biomes) change as altitude increases. For example, Arizona's elevation ranges from the low point along the Colorado River at 21 m to the highest point, Humphreys Peak, at 3,850 m (including mountainous regions), making Arizona's biomes drastically unique from one another. Namely, they are the desert, grassland, chaparral, woodland, forest, and tundra.


Elev. m
4000
3000
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S
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Arizona vegetation types
BIOMES
MERRIAM'S LIFE ZONES
BOREAL FOREST
HUDSONIAN
FIR FOREST
CANADIAN
PONDEROSA PINE FOREST
TRANSITION
DRY WOODLANDS & CHAPARRAL
OAK PINE WOODLAND
UPPER SONORAN
OAK WOODLAND AND CHAPARRAL
DESERT-GRASSLAND
DESERT
LOWER SONORAN
DESERTSCRUB

Figure 1: This diagram (UofArizona Antevs Library) shows the differences of Arizona biomes as a function of elevation. Evidently, as elevation increases, temperature decreases (and precipitation typically increases as well), resulting in different vegetation types such as desert scrub and grasslands etc.

Biomes in Arizona

The desert biome (100–3,500 ft) is mostly in southwest Arizona, for example, in the Sonoran, Mojave, and Chihuahuan deserts. In particular, the Sonoran Desert is thought to be home to the greatest variety of species of animals and plants in all deserts in North America (NPS [Sonoran Desert Network Ecosystems], 2023). Deserts are defined by low precipitation (usually less than 50 cm of annual rainfall), hot summers, and mild winters. However, despite these harsh conditions, many species of organisms can evolve unique traits and lifestyles to help them survive and thrive, including the saguaro cacti, palo verde, and wildlife like lizards, tortoises, and kangaroo rats (UofArizona Antevs Library).

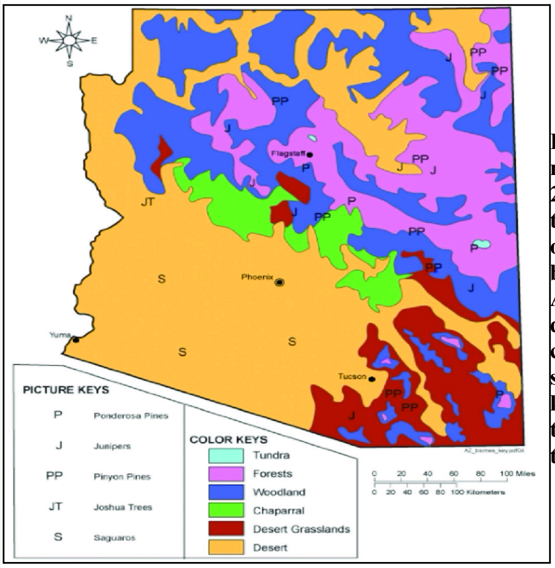
Next, at slightly higher elevation, the Grassland Biome (3,300–7,000 ft) spans central and eastern Arizona. This biome has warm summers, cold winters, and moderate rainfall. Some common vegetation in the Grassland biome would include yucca, gramma, and wheatgrass (UofArizona Antevs Library). Since there's so much vegetation, it is a good habitat for grazing animals, nesting birds, and predators like coyotes and hawks. The Grassland biome has conditions that are between the arid desert and the mountains.

Moreover, Chaparral biomes (4,000–6,000 ft) are located between the desert and the mountain regions, especially on mountain slopes. Having warm, dry summers and cool, wet winters, this biome includes sugar bush, manzanita, and other dense shrubs (UofArizona Antevs Library). Since fires are actually part of chaparral ecosystems, many plants there are fire-adapted, so they're able to quickly grow back quickly if burned.

Woodland Biome (5,000–7,000 ft) is often found near mountainous regions and is also similar to Chaparral biomes, being in between desert and mountain regions as marked in Figure 2. Plants and vegetation that grow in woodland include juniper, oak, and pinyon pine (UofArizona Antevs Library). Woodlands have more precipitation and cooler temperatures than deserts, which allows them to have larger trees and more diverse animal life, including deer, foxes, and various types of birds.

The forest biome (6,900–10,500 ft) is located mostly in the highlands of northeastern Arizona. These areas receive significant amounts of snow and rain, providing enough moisture, and high, dense trees create open understories, allowing grasses, shrubs, forbs, and broadleaf trees to grow under them (Arizona Game and Fish Department). The rich soils make it possible for forests to support large mammals like elk and black bears, as well as birds.

Last but not least, alpine tundra (11,000–12,670 ft) is only applicable to the two highest peaks in Arizona, both of which are in the San Francisco Mountains in northern Arizona. The temperature is extremely cold year-round, with short growing seasons and high snow precipitation. Instead of trees, plants like grasses, alpine timothy, lichens, sibbaldia, and mosses grow here (Arizona Game and Fish Department; UofArizona Antevs Library). Of course, this means the plants and animals that are part of this biome must be able to withstand wind, cold, and thin air.


N
W
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Flagstaff
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Yuma
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JT
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S
PICTURE KEYS
P Ponderosa Pines
J Junipers
PP Pinyon Pines
JT Joshua Trees
S Saguaros
COLOR KEYS
Tundra
Forests
Woodland
Chaparral
Desert Grasslands
Desert
0 20 40 60 80 100 Miles
0 20 40 60 80 100 Kilometers

Figure 2: This map (Bodini, 2024) reports the locations of different biomes of Arizona using different colors, as shown in the key noted at the bottom of the figure.

The Sonoran Desert

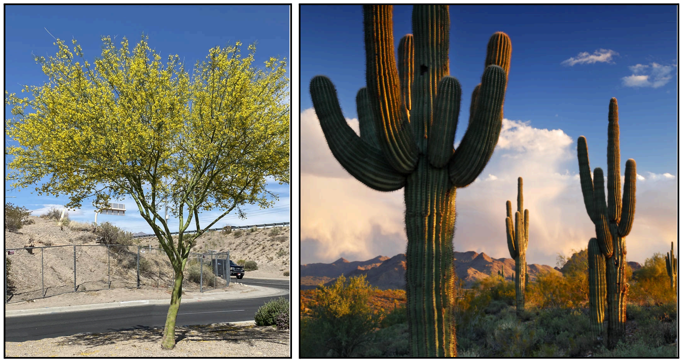
Most of Central Arizona's ecosystem is part of the Sonoran Desert biome. The Sonoran Desert, which spans approximately 260,000 square kilometers, occupies most of northwest Mexico, southern and Central Arizona, and southeastern California (NPS [Sonoran Desert Network Ecosystems], 2023). As a desert, the Sonoran often has extreme weather. For example, summer air temperatures in the Sonoran routinely went above 40°C, and often reached 48°C, and even during any season, it's very common for the desert temperature to swing 15°C or more (NPS [Sonoran Desert Network Ecosystems], 2023).

Specifically, the Sonoran Desert is noted for its rainfall pattern, where rain occurs in the winter, which is frequent and relatively low intensity, while there is another, more violent, "monsoon" season, during the summer. For the former, in around December and January, usually, it's due to winter storms being blown into the Great Plains region from the Pacific Northwest and clashes with accumulated low pressures that were formed over the western U.S., and the storms get pushed south along the west coast, across the Sonoran Desert (Basics of the Arizona Monsoon & Desert Meteorology, n.d; NPS [Sonoran Desert Network Ecosystems], 2023). For the latter, since the primary wind flow into Arizona, which maintains its dry conditions most of the year, when the winds shift toward southerly winds during June and July, it would bring in moisture and trigger summer thunderstorms (NPS [Sonoran Desert Network Ecosystems], 2023).

However, despite the harsh climate of the Sonoran Desert, living organisms have developed unique ways of surviving and thriving. For example, Palo Verde, a type of small tree that grows in the Sonoran desert, has green bark that contains chlorophyll, which allows it to photosynthesize even when the tree has shed its leaves when the climate is hot and dry (Schuch & Kelly, 2008). This way, the tree can still store energy in its roots, giving it access to any underground water supply. Palo Verde also contributes to surrounding ecosystems, including preventing soil erosion with its deep roots and providing shelter and food to wildlife species in the biome.(Schuch & Kelly, 2008).

Many other desert plants have shown similar characteristics and adaptations as well. For example, the saguaro cactus has pleated stems that expand as it absorbs water, allowing it to store as much water as possible during rainy seasons through its shallow roots (NPS [The Saguaro Cactus], 2024). Saguaros can live for over 150 years and support an entire mini-ecosystem—birds such as Gila woodpeckers and elf owls nest in the cavities of the cactus flesh, while the mammals like bats eat the cactus fruit during the summer (NPS [The Saguaro Cactus], 2024).

Figure 3 (below): Left: Palo Verde; Right: Saguaro Cactus



Left: https://guzmansgreenhouse.com/the-palo-verde-tree-desert-museum/
Right: https://www.visitphoenix.com/sonoran-desert/saguaro-cactus/

Additionally, desert animals have also evolved unique lifestyles/traits to survive. Many animals, including kangaroo rats, rarely need to drink water at all because they get moisture from their food and remain underground during the hottest parts of the day (NPS [Kangaroo Rats], 2023). Reptiles like the Gila monster, one of only a few venomous lizards in the world, store fat in their tails and spend much of the year in burrows and are only active above ground if the conditions are cooler and less hot (NPS [Gila Monster], 2024). Not only that, but in fact, many animals and insects in the desert are often nocturnal because the temperatures are lower at night.

Climate Change's Effect on Desert Biomes

However, climate change is real. As global temperatures increase, native species of the Sonoran desert are under thermal stress (especially in the desert) (Bachelet et al, 2015).

More specifically, Bachelet and colleagues (2015) conducted research analyzing the effects of climate change on southern California deserts (namely the Mojave and Sonoran) and were able to make three future predictions on the state of the deserts. First, across all climate models, temperatures are expected to increase by more than 2°C by midcentury (Bachelet et al, 2015). Now, under the possibility of a hotter and drier future climate (CanESM2 model), simulations showed a substantial decrease in herbaceous vegetation and instead an increase in desert land, especially in the Sonoran and Mojave deserts (Bachelet et al, 2015). In contrast, a wetter future climate (MIROC5 model) showed short-term increases in green vegetation but would increase the population of shrubs and invasive species in the biome because of the current high climate velocity, which is the speed at which the climate is changing over time (Bachelet et al, 2015). Unfortunately, in low areas such as the desert, the climate changes faster than what native species can migrate or adjust, so these species are at higher risk of extinction or dying in mass amounts. Additionally, the pollination cycles of desert plants could also be disrupted by changes in climate because many species of plants rely on the rainy seasons to pollinate and reproduce.

References

Bachelet, D., Ferschweiler, K., Sheehan, T., & Strittholt, J. (2016). Climate change effects on Southern California deserts. *Journal of Arid Environments*, *127*, 17–29. https://doi.org/10.1016/j.jaridenv.2015.10.003

Basics of the Arizona Monsoon & Desert Meteorology. School of Geographical Sciences and Urban Planning ASU. (n.d.). https://sgsup.asu.edu/basics-arizona-monsoon-desert-meteorology#:~:text=The%20North%20American%20Monsoon%20in,level%20moisture%2C%20triggering%20summer%20thunderstorms.

Bodini, M. (2024). Charting the future of conservation in Arizona: Innovative strategies for preserving its natural resources. *Conservation*, *4*(3), 402–434. https://doi.org/10.3390/conservation4030027

Forest and Woodland Overview. Arizona Wildlife Conservation Strategy. (n.d.). https://awcs.azgfd.com/chapter-7-habitat-profiles/forest-and-woodland-overview

Schuch, U., & Kelly, J. (2008). Palo Verde Trees for the Urban Landscape. *Bulletin of The Desert Legume Program of The Boyce Thompson Southwestern Arboretum and The University of Arizona ARIDUS*, *20*(1). https://doi.org/https://cales.arizona.edu/desertlegumeprogram/sites/cals.arizona.edu.desertlegumeprogram/files/aridus20-1.pdf

U.S. Department of the Interior. (2023a). *Kangaroo rat*. National Parks Service. https://www.nps.gov/orpi/learn/nature/kangaroo-rat.htm#:~:text=Who%20are%20They?,live%20and%20hide%20in%20burrows.

U.S. Department of the Interior. (2023b). *Sonoran Desert Network Ecosystems (U.S. National Park Service)*. National Parks Service. https://www.nps.gov/im/sodn/ecosystems.htm#:~:text=The%20Sonoran%20Desert%20occupies%20approximately,Baja%20and%20the%20mid%2Dcontinent.

U.S. Department of the Interior. (2024b). *Gila Monster*. National Parks Service. https://www.nps.gov/sagu/learn/nature/gila-monster.htm

U.S. Department of the Interior. (2024c). *The Saguaro Cactus*. National Parks Service. https://www.nps.gov/sagu/learn/nature/saguaro.htm

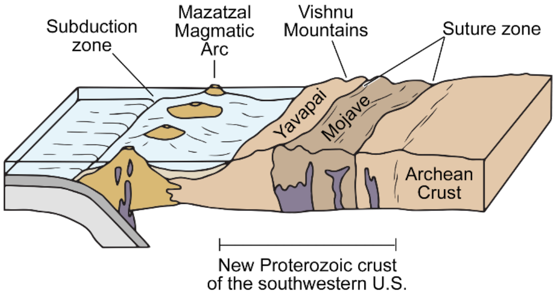
Payson ophiolite
Amanda Bednarick

We are in Central Arizona in a region known as the transition zone, which marks the boundary between two major tectonic provinces in today's North America – the Colorado Plateau and the southern Basin and Range.

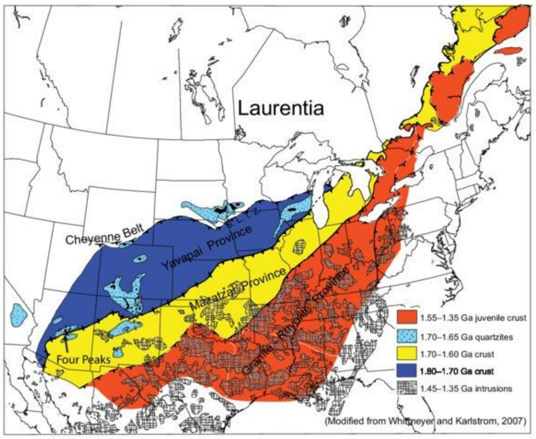
Payson, Arizona hosts an ophiolite, which is a sliver of ancient oceanic crust. To understand how seafloor ended up in the middle of Arizona we need to review the Proterozoic geology of the southwest USA.

During the Paleoproterozoic, there were active subduction zones southeast of Laurentia, the North American craton. The resulting island arc magmatism generated new subaerial terranes of mantle-derived igneous rock. As this geodynamic regime persisted over many millions of years, several of these terranes were built, subparallel to paleosubduction. During the Yavapai and Mazatzal orogenies (1.8-1.6 Ga), these island arc terranes got metamorphosed, intruded by granites, and smushed up against the edge of the North American craton.

Less is known about the remaining Precambrian era (1.4 billion years ago until 600 million years ago) because deposits from this time are missing from the geologic record. This "missing time" is marked by the Great Unconformity.


Subduction zone
Mazatzal Magmatic Arc
Vishnu Mountains
Suture zone
Yavapai
Mojave
Archean Crust
New Proterozoic crust of the southwestern U.S.

← Schematic of subparallel island arc terranes to be accreted to North America


Laurentia
Cheyenne Belt
S. L. T. Z.
Yavapai Province
Mazatzal Province
Granite - Rhyolite Province
Four Peaks
1.55–1.35 Ga juvenile crust
1.70–1.65 Ga quartzites
1.70–1.60 Ga crust
1.80–1.70 Ga crust
1.45–1.35 Ga intrusions
(Modified from Whitmeyer and Karlstrom, 2007)

^ the result: North America is not just continental craton: a lot of "oceanic," mantle-derived material accreted.

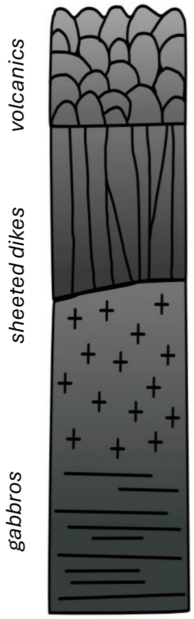
← Field camp pic of the Great Unconformity exposed in Wyoming

The Payson ophiolite is a very old example of a mostly continuous section of oceanic crust. It probably formed in a backarc basin associated with the aforementioned island arc magmatism. Identifying and mapping old oceanic terranes is key to reconstructing tectonic histories.

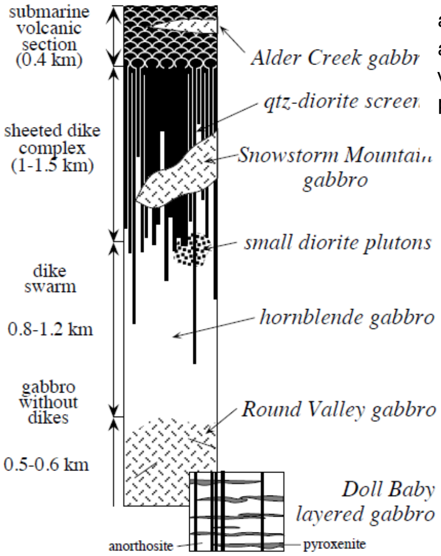
Importantly, the ophiolite's existence and interpretation tells us that spreading centers were active on Earth at 1.7 Ga. This is a nontrivial implication – spreading centers (like mid-ocean ridges) are indicative of modern-style plate tectonics, the history of which remains a contentious subject.

Normally, basaltic seafloor is generated at mid-ocean ridges, rides a "conveyor belt" across the ocean for some tens of millions of years, and then arrives at a plate boundary and is subducted back into the interior of the Earth, never to be exposed or studied. Ophiolites are exceptional in that they are slivers of oceanic crust that escaped this subductive fate. Somehow these chunks get preserved on land and can grow old. The Payson ophiolite is almost a whole order of magnitude older than the oldest extant oceanic crust, which provides a rare opportunity to study the structure and geochemistry of this important class of rock beyond the Mesozoic. I am using Sr and O isotopes to try to probe hydrothermal alteration processes during the Paleoproterozoic. Because of probable differences in e.g. seawater chemistry and mantle temperatures compared to today, it is not clear how these geochemical cycling regimes were operating in the very distant past.

Expectations


volcanics
sheeted dikes
gabbros

Reality


submarine volcanic section (0.4 km)
sheeted dike complex (1-1.5 km)
dike swarm
0.8-1.2 km
gabbro without dikes
0.5-0.6 km
Alder Creek gabbr
qtz-diorite screer
Snowstorm Mountai
gabbro
small diorite plutons
hornblende gabbro
Round Valley gabbro
Doll Baby
layered gabbro
anorthosite
pyroxenite

← what ophiolites look like in cross section: the characteristic "pseudostratigraphy" that arises from a pile of basaltic material cooling at a spreading center with a thermal gradient, versus a real-life example – pseudostratigraphy of the Payson ophiolite.

References

Jesse Dann, 1997, GSA Bulletin

Mako et al., 2015 Geosphere

Wade Greenberg-Brand (adapted from an image by Karlstrom et al. 2012, *Geological Society of America Special Papers* 489, pp. 7–24) originally published in *The Teacher-Friendly Guide to the Earth Science of the Southwestern US*.